

Optimization of Small-Capacity STPs (0.5–5 MLD) Using Hybrid Treatment Technologies

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ABSTRACT- STPs with small capacities (0.5-5 million liters per day (MLD)) play a trivial role in the decentralized treatment of wastewater in small and medium towns. This paper will compare traditional activated sludge process (ASP) with five hybrid systems, which include MBBR-SBR, IFAS-MBBR, SBR + constructed wetlands (CW), MBBR + CW and IFAS + CW. The characteristics presentation of representative Indian domestic sewage (BOD 2500-400 mg/L, COD 500-800 mg/L, TN 3060 mg/L and TP 5-10 mg/L) were taken at the design capacities of 0.5, 1, 2 and 5 MLD. The performance based on simulation took into account the removal of pollutants, energy consumption, life-cycle cost, land requirement, the carbon footprint, and sludge generation. Multi-criteria decision analysis (MCDA) using TOPSIS ranked IFAS + CW as the best, then MBBR + CW (0.895), and IFAS-MBBR (0.868). The modeled BOD and COD removal was the highest with IFAS-MBBR, although, CW-integrated systems needed less energy and produced less modeled carbon emissions and sludge. The findings show that the configuration of choice would depend on the relative significance of treatment efficiency, land, energy and cost; then based on the specified MCDA weights, IFAS + CW would give the best overall tradeoff to small, capacity decentralized STPs.

KEYWORDS—Small-Capacity STP, MBBR, SBR, IFAS, Constructed Wetlands, Life-Cycle Cost, MCDA, TOPSIS, Decentralized Wastewater Treatment, Sustainability

I. INTRODUCTION

The rapid urbanization has grown wastewater production without making sure that centralized treatment facilities are well-sized in many of the small and medium towns. Local treatment and reuse can be facilitated by decentralized STPs that cut down on the conveyance requirements. The traditional ASP is still in use but a variable hydraulic and organic load, energy requirement, sludge generation and space needs may pose a problem of operation at small scale [4]–[11].

Hybrid systems are systems that are a blend of complementary mechanisms. MBBR is able to establish active biofilm on carriers and also offer compact biological

treatment [1], [6]. SBR gives flexibility in operation as a variable loading process, and has the capacity of supporting nutrient removal [10]. IFAS incorporates both suspended and attached growth and may enhance better biomass retention and nitrification [2], [14]. Additional nutrient removal hybrid biological arrangements are also explored [1]. Wetlands built low-energy polishing and may serve to help with the removal of nutrients and decentralised reuse-oriented treatment [12], [15] [16] [17]. Past research has typically focused on each technology separately or more broad urban facilities. The current analysis is concerned with 0.5-5 mld and it combines the performance of treatment, energy, costs of life-cycle and environment in one MCDA model. The primary goal is to find the optimal configuration that will give the optimal overall compromise given the design assumptions and weighting of the criteria.

II. LITERATURE REVIEW

MBBR, SBR and IFAS are established biological-treatment approaches for municipal wastewater. MBBR offers high biomass concentration and compact reactor volume, while SBR provides operational flexibility for variable flows [6], [10]. IFAS can enhance nitrification and process stability by combining attached and suspended biomass [2], [14].

Constructed wetlands are increasingly considered as polishing or decentralized treatment units because they can reduce energy demand and provide additional nutrient removal. Reviews have reported their treatment performance, low operation and maintenance requirements, and life-cycle-cost relevance [17]. Indian studies have also reported the technical, economic, and life-cycle relevance of hybrid and decentralized systems [5], [8], [9], [11], [12]. Technology selection therefore involves trade-offs: compact mechanized systems generally require less land, whereas CW-integrated systems can reduce energy use and operating costs [5], [12], [17].

A focused literature search was considered for publications from 2015–2025 using Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. The search focused on small-capacity STPs, hybrid treatment technologies, MBBR, SBR, IFAS, constructed wetlands,

energy consumption, life-cycle cost, and decentralized wastewater treatment. The selected literature was used to establish representative performance ranges and assumptions for the comparative assessment. The study is a simulation-based comparative assessment and does not claim a formal systematic review or meta-analysis.

III. MATERIALS AND METHODS

A. Study design and design basis

The simulation study was comparative in nature and comprised of STPs that had design capacities of 0.5, 1, 2 and 5 MLD. Representative influent characteristics were BOD 250–400 mg/L, COD 500–800 mg/L, TSS 200–400 mg/L, TN 30–60 mg/L and TP 5–10 mg/L. The effluent values targeted in the original study study were BOD <30 mg/L, COD <250 mg/L, TSS <50 mg/L, TN <10 20 mg/L and TP <1 2mg/L.

Peak-flow and average-flow differences of 2.5 and ± 2030 percent, respectively, were taken into consideration. HRT, SRT, MLSS and DO had diversification, within technology-appropriate ranges. Six of the following alternatives are compared in the study: ASP, MBBR-SBR, IFAS-MBBR, SBR + CW, MBBR + CW and IFAS + CW.

B. Performance assessment

Removal efficiency was determined as $\eta = (C_1 - C_3 / C_1) \times 100$. C_1 was the concentration in the influent and C_3 was the focus concentration in the effluent. Substrate utilization and nitrification-denitrification were modeled as biological removal based on conventional kinetic idealizations of these processes. Energy requirements were aeration, pumping, mixing and sludge handling. Since the manuscript lacks values of all kinetic constants and reactor-specific calibration parameters, the values are to be

viewed as a simulation based comparative estimates but not a full-scale experiment value.

C. Life-cycle cost and sustainability test.

Life-cycle cost was calculated in the 20 years based on CAPEX, annual OPEX, the cost of land and a discount number ranging between 8 and 10 as it is in the original study. Indexes of the environment were energy use, land surface, carbon footprint and sludge production. Life-cycle environmental methods have also been used to assess integrated treatment systems that incorporate constructed wetlands [19]. These LCC values are reported as outputs of the model; in the source manuscript the entire project cash-flow schedule was not given.

D. MCDA and sensitivity analysis.

Topsis was implemented with the help of six criteria, including BOD removal (20%), COD removal (20%), TN removal (15%), TP removal (15%), energy consumption (15%), and life-cycle cost (15%). Removal criteria were considered as benefit criteria and energy and cost were considered as cost criteria. To compute the decision matrix $X = [x]$. The normalization of vectors was done through vector normalization $r_x = x / \sqrt{\sum x^2}$ and the weighting of the vectors: $v = w r$. The ideal solutions (positive and negative), were then labeled as positive and negative, or rather the coefficient of relative proximity was provided as $C_n = S_n - S_n^- / S_n + S_n^-$. When C_2 is bigger, it is closer to the optimal solution. The method adheres to the existing wastewater-technology selection applications of TOPSIS [18]. Sensitivity was studied with changing influent load, cost of land and cost of energy. Since they did not provide an independent dataset of plants to test, the outcome is seen as relative model estimates but not experimentally valid outcomes.

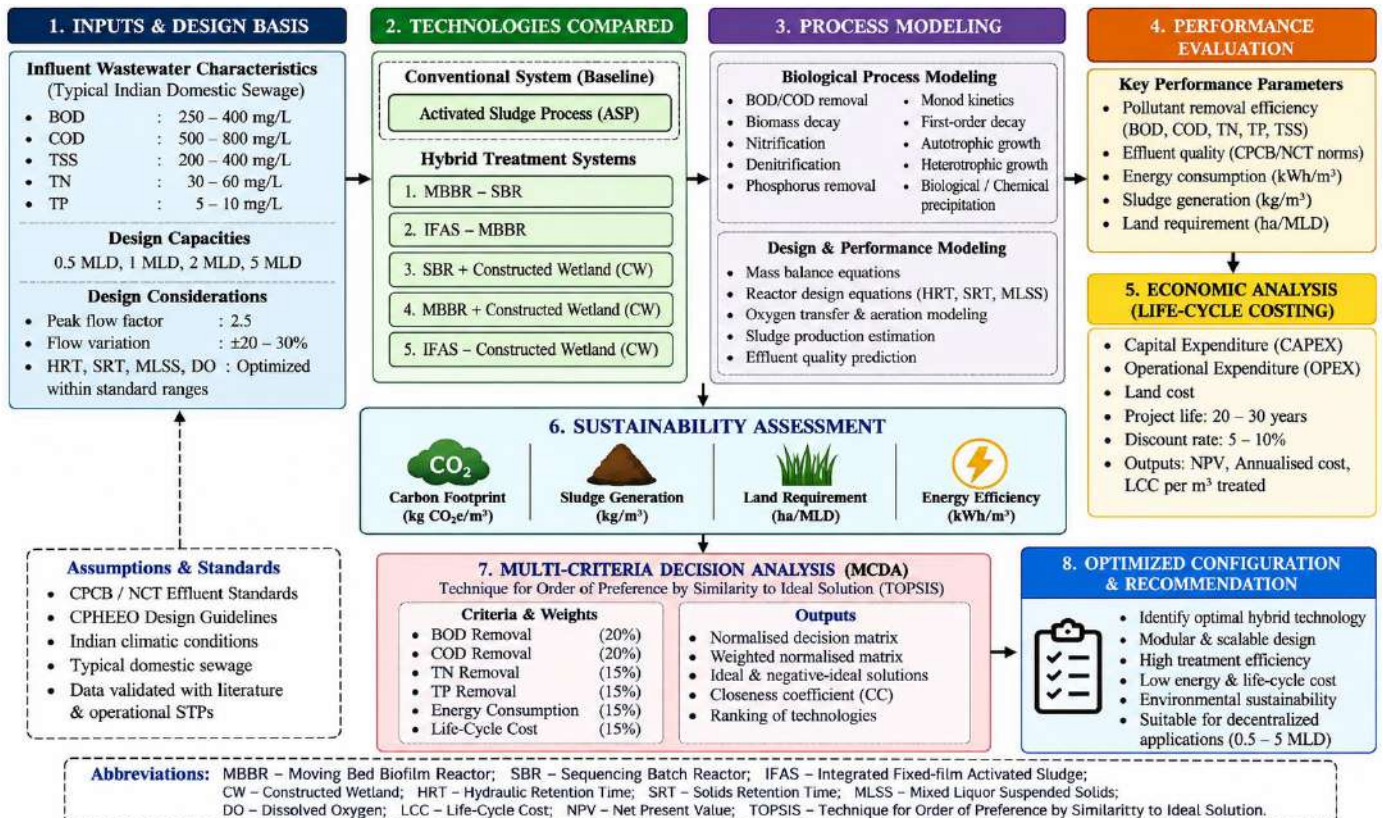


Figure 1: Technology-selection and process-modeling framework used for the comparative assessment.

Figure 1 shows a combined scheme to the design, comparison, modeling, assessments, economic analysis, sustainability analysis and optimization of small capacity sewage treatment plants (STPs) between 0.5 and 5 MLD. The framework involves a step-by-step decision-making process where wastewater characteristics and design specifications compare the treatment technologies, model their performance, test the economic and sustainability parameters and eventually pick the desired treatment configuration through Multi-Criteria Decision Analysis (MCDA) relying on TOPSIS.

The structure starts with Step 1: Inputs and Design Basis in which the common Indian domestic wastewater peculiarities are taken into account. These include BOD of 250–400 mg/L, COD of 500–800 mg/L, TSS of 200–400 mg/L, TN of 30–60 mg/L, and TP of 5–10 mg/L. The design capacities to be taken are 0.5, 1, 2 and 5 MLD. A peak-flow factor of 2.5, a flow variation of about 20–30 and optimization of HRT, SRT, MLSS, and dissolved oxygen are important design considerations.

In Step 2: Technologies Compared, the framework has established a standard Activated Sludge Process (ASP) as a benchmark and from that, it has compared it with 5 hybrid treatment options: MBBR SBR, IFAS MBBR, SBR Constructed Wetland (CW), MBBR Constructed Wetland, and SBR IFAS Constructed Wetland. This will enable the alternative treatment systems to be measured against standard and hybrid systems.

Step 3: Process Modeling is the biological and engineering modeling step. The biological processes considered in the framework include the BOD/COD removal, biomass decay, nitrification, denitrification, and phosphorus removal. It also introduces design and performance modeling in the form of mass-balance equations, reactor design equations, oxygen-transfer requirements, estimate sludge-production, and prediction of effluent-quality.

Step 4: Performance Evaluation follows the modeling of systems, and the parameters used to evaluate the systems include pollutant-removal efficiency of systems on BOD, COD, TN, and TP; compliance of effluents quality; energy usage; sludge generation; land requirement. The indicators will give the technical basis of the comparison of the treatment options.

Step 5: Economic Analysis-Life-Cycle Costing- The Life-Cycle Costing calculates the economical side of every option. The analysis takes into account the capital expenditure (CAPEX), operational expenditure (OPEX), land cost, the 20 to 30 years project life and 5–10 discount rate. The economic indicators which would be obtained are NPV, annualized cost and life-cycle cost (LCC).

Step 6: Sustainability Assessment is also part of the framework and involves the assessment of environmental and other resource-related metrics such as carbon footprint, sludge generation, land requirement and energy efficiency. These indicators are supplementary as compared to the technical and economic performance measures.

In Step 7: Multi-Criteria Decision Analysis (MCDA), TOPSIS is used in order to bring about the various evaluation criteria. The criteria and their weightings are: BOD removal (20%), COD removal (20%), TN removal (15%), TP removal (15%), energy consumption (15%), and life-cycle cost (15%). TOPSIS generates weighted and normalized ideals-anti-ideals features, proximity coefficients, and an ultimate ranking of the treatment options.

Lastly, Step 8: Optimized Configuration & Recommendation determines the most appropriate treatment configuration using the technical, economic, and sustainability analysis. The chosen setup would give high treatment efficiency, reduced energy and life-cycle costs, enhanced environmental sustainability, as well as being applicable to decentralized small-capacity STPs.

The framework is further informed by assumptions and standards such as CPCB/NCT effluent standards, CPHEEO design guidelines, Indian climatic conditions, common domestic sewage traits, and data that is checked against the literature and proven STPs. Therefore, the figure offers an end-to-end route available to enter into wastewater inputs, choice of technology, process representation, multi-dimensional analysis, TOPSIS ranking and eventual treatment-technology selection.

IV. RESULTS AND DISCUSSION

A. Pollutant removal

Pollutant removal SS configurations yielded greater modeled pollutant-removal ranges as compared to ASP. The greatest BOD and COD removal was observed in IFAS-MBBR and CW-integrated systems had a competitive nutrient removal such as IFAS + CW and others. These findings justify the application of hybrid attached-growth and nature-based processes in cases where balancing between performance of a treatment process and energy/sustainability need to be considered. Table 1 is a summary of the modeled removal ranges.

Table 1: Modeled pollutant-removal performance across 0.5–5 MLD

Technology	BOD (%)	COD (%)	TN (%)	TP (%)
ASP	88–92	82–87	50–65	40–55
MBBR-SBR	94–97	91–94	75–85	60–75
IFAS-MBBR	96–97	93–95	80–88	65–80
SBR + CW	92–96	88–93	70–82	55–75
MBBR + CW	93–96	89–93	72–84	60–78
IFAS + CW	94–97	91–94	75–86	65–80

Table 1 shows the computationalized BOD, COD, TN, and TP removal ranges of the six treatment options, as well as the primary performance comparison which interprets the results.

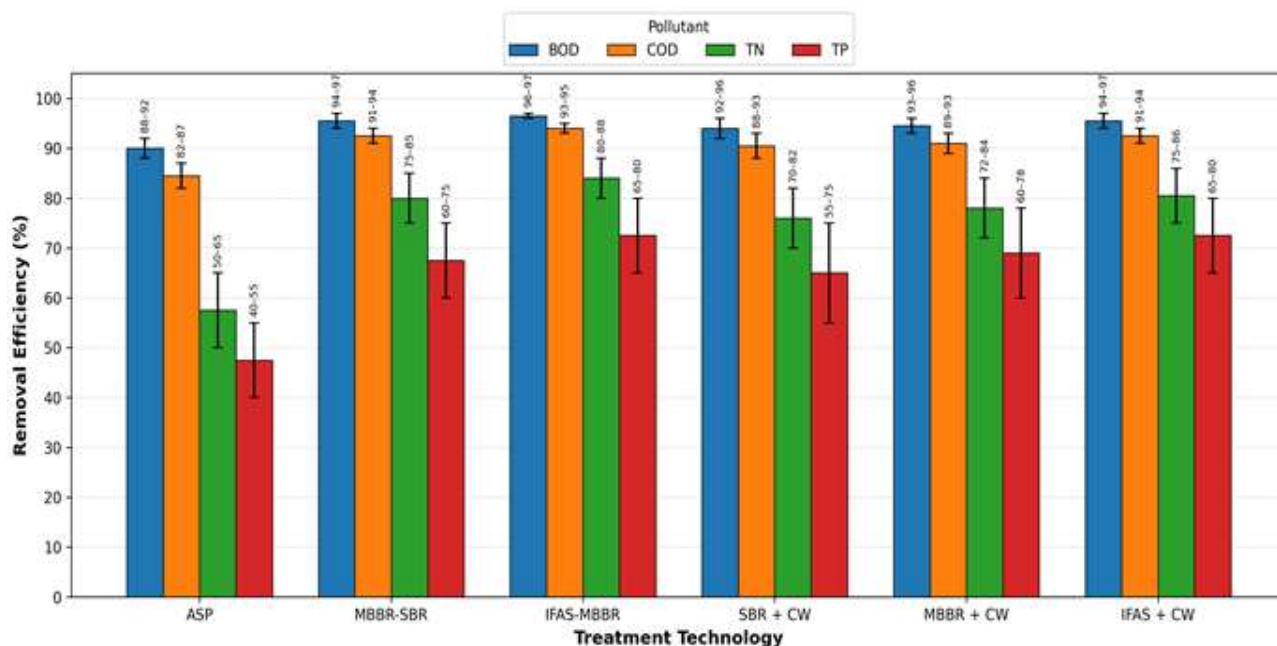


Figure 2: Small-scale treatment (0.5 to 5 MLD) comparison of treatment technology performance in terms of pollutant removal

The effectiveness of BOD, COD, TN and TP removal in the six treatment runs is compared in Figure 2. IFAS-MBBR models a better BOD and COD removal, competitive is CW-integrated systems that display competitive nutrient-removal performance.

B. Energy consumption

The key operating parameter of dec-STPs is energy consumption. The analyzed results indicate that CW-integrated formats require less energy, as some part of the polishing process would be available without active mechanical aeration. Table 2 summarises the values modeled.

Table 2: Modeled energy consumption

Technology	Energy consumption (kWh/m ³)
ASP	0.60–0.80
MBBR-SBR	0.45–0.55
IFAS-MBBR	0.40–0.50
SBR + CW	0.25–0.40
MBBR + CW	0.20–0.35
IFAS + CW	0.18–0.32

Table 2 presents a summary of the energy demand that is modeled of each treatment configuration. Redder values mean a reduction in operation energy.

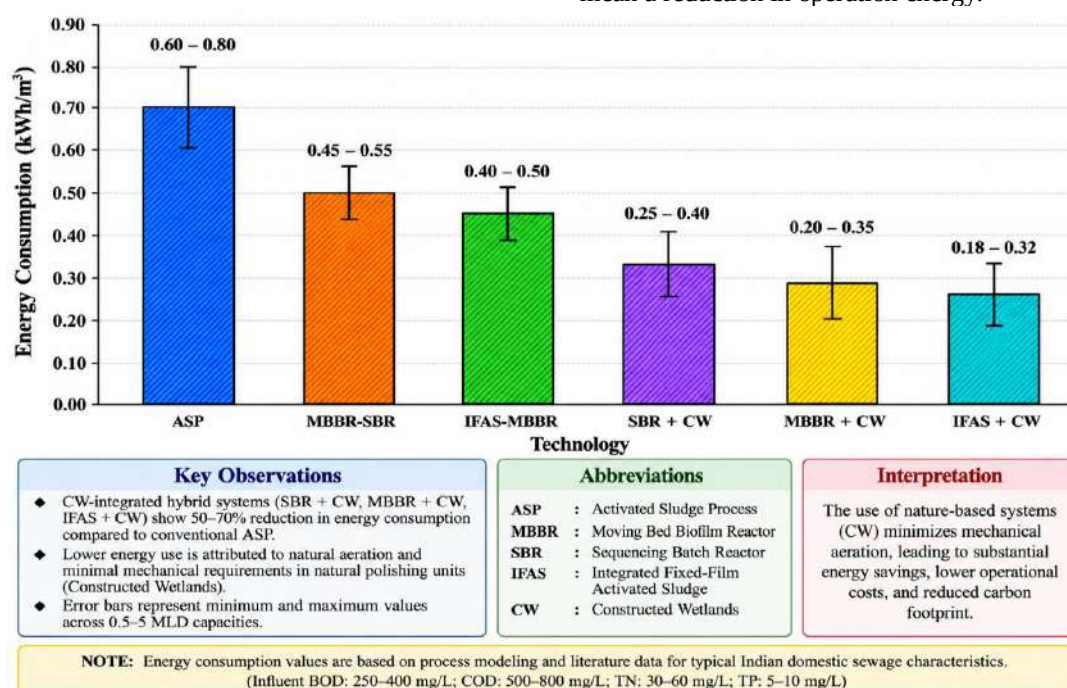


Figure 3: Comparative modeled energy consumption across the evaluated treatment configurations

The data indicated in Figure 3 depict that ASP consumes the most energy of all the modeled systems and CW-integrated systems use significantly less energy. The figure of IFAS + CW lies the lowest (0.18-0.32 kWh/m³), meaning that this does the most to decrease the operational energy demand.

C. Life-cycle cost

In the case of 2 MLD, the initial model predicted smaller combinations of CAPEX/OPEX and reduced total LCC with CW-integrated systems as compared to ASP one. Since the original manuscript lacks a fully detailed discounted cash-flow schedule, these values are not recalculated as the independent output of a financial value, but rather as the output of a comparative model. Table 3 gives ranges of the costs.

The modeled CAPEX, per annum OPEX, 20 years life-cycle cost, and LCC per cubic metre of the 2 MLD case are shown in Table 3. The values are not audited costs of projects but model outputs that are comparative to each other

Table 3: Reported model-based CAPEX, annual OPEX and 20-year LCC for a 2 MLD example

Technology	CAPEX (₹ lakh)	Annual OPEX (₹ lakh)	20-year LCC (₹ lakh)	LCC/m ³
ASP	450–550	65–85	1850–2250	2.8–3.4
MBBR-SBR	520–620	45–55	1450–1750	2.1–2.6
IFAS-MBBR	550–650	40–50	1380–1680	2.0–2.5
SBR + CW	480–580	28–38	1180–1480	1.7–2.2
MBBR + CW	460–560	25–35	1120–1420	1.6–2.1
IFAS + CW	470–570	22–32	1080–1380	1.55–2.0

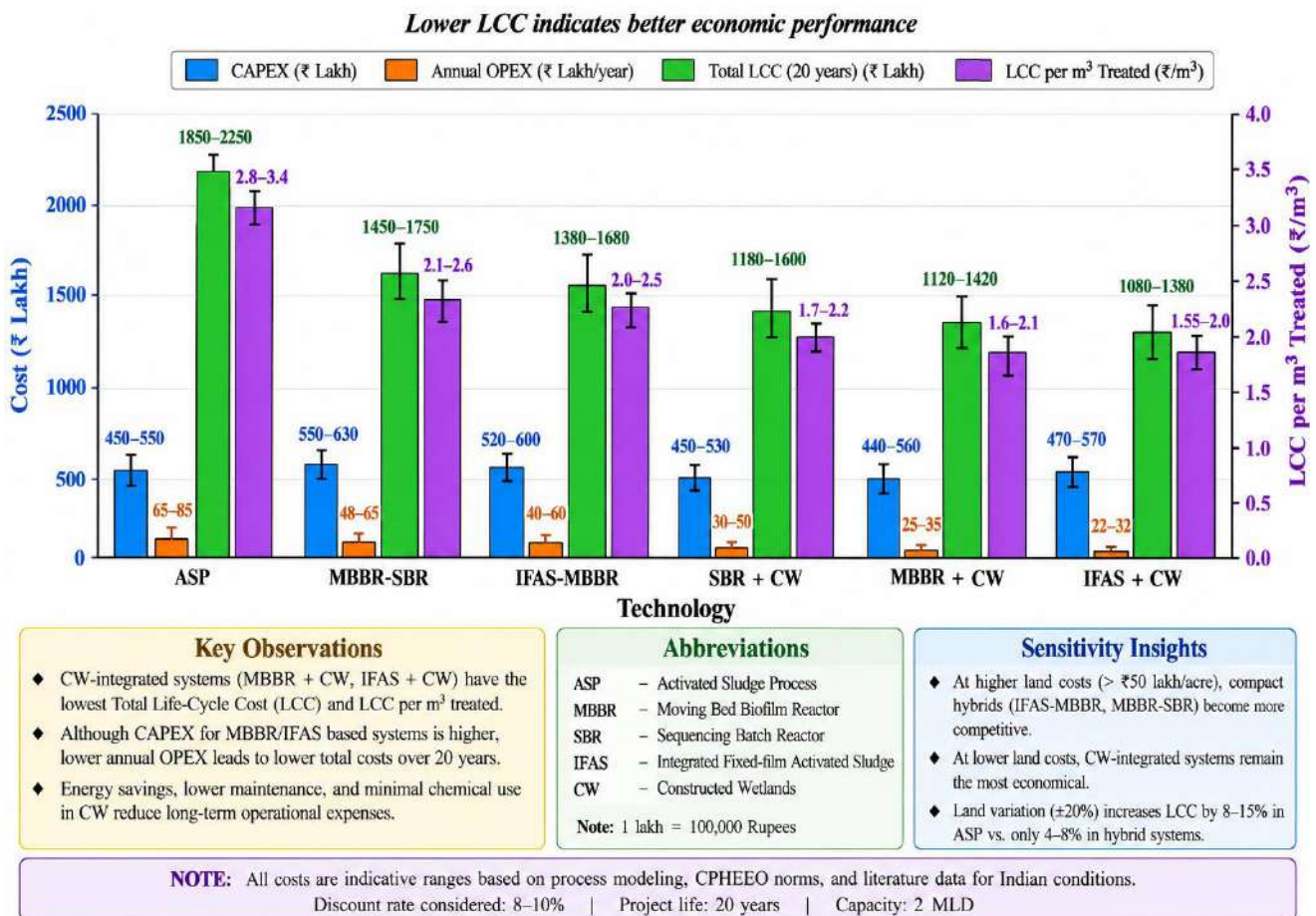


Figure 4: Comparative life-cycle cost indicators for the six treatment configurations

Figure 4 shows a comparison between CAPEX, annual OPEX, 20 years total LCC, and LCC per cubic metre treated. The total LCC/LLC per m³ are lowest in IFAS + CW, and highest in ASP which is the life-cycle cost modeled.

According to the model, CW-integrated systems are reasonably cheap when there is the availability of adequate land. Compactness benefit of IFAS-MBBR and MBBR-SBR is of more significance in high land price. This is a

trade-off of the land, energy and cost that has to be considered when it comes to siting specification.

D. TOPSIS-based MCDA

TOPSIS was utilized (treatment performance, energy and cost) and added together to form a single decision score. The weights total 100%. The closeness coefficients obtained above identify IFAS + CW as the most preferred choice with the weights of the above.

The provided result solidifies the discrepancy between the initial text: MBBR-SBR-CW is not mentioned as the most suitable one because it is not shown as a distinct treatment in the decision table. The Table 4 has shown the normalized scores and ranks.

Table 4: TOPSIS normalized scores and ranking of the evaluated treatment alternatives

Technology	BO D	CO D	TN	TP	Ener gy	LC C	TOPS IS rank
ASP	0.72	0.70	0.55	0.48	0.35	0.40	6
MBBR-SBR	0.92	0.90	0.80	0.68	0.65	0.70	5
IFAS-MBBR	0.96	0.94	0.85	0.73	0.70	0.72	3
SBR + CW	0.88	0.85	0.76	0.65	0.82	0.85	4
MBBR + CW	0.90	0.87	0.78	0.69	0.85	0.88	2
IFAS + CW	0.93	0.91	0.81	0.72	0.88	0.90	1

Table 4 presents the normalized TOPSIS scores and final ranking obtained using the six weighted decision criteria. Higher scores indicate greater proximity to the preferred overall performance.

The corresponding closeness coefficients were 0.512 (ASP), 0.795 (MBBR-SBR), 0.868 (IFAS-MBBR), 0.842 (SBR + CW), 0.895 (MBBR + CW) and 0.912 (IFAS + CW).

Therefore, IFAS + CW is the selected overall configuration for the stated weights. The ranking should be interpreted as a decision-model result, not as an experimental proof that one technology is universally superior.

E. Sustainability assessment

Table 5: Sustainability indicators for the evaluated treatment technologies (0.5–5 MLD)

Technology	Energy (kWh/m ³)	Land (ha/MLD)	Carbon footprint (kg CO ₂ e/m ³)	Sludge (kg/m ³)
ASP	0.70	0.4–0.6	0.65–0.85	0.25–0.35
MBBR-SBR	0.50	0.25–0.35	0.45–0.60	0.18–0.25
IFAS-MBBR	0.45	0.20–0.30	0.40–0.55	0.15–0.22
SBR + CW	0.32	0.8–1.2	0.25–0.40	0.10–0.18
MBBR + CW	0.28	0.7–1.0	0.22–0.35	0.09–0.16
IFAS + CW	0.25	0.65–0.95	0.20–0.32	0.08–0.15

Table 5 summarizes the modeled sustainability indicators, including energy consumption, land requirement, carbon footprint, and sludge generation. These values are indicative model-based comparisons and should be interpreted within the stated assumptions.

(Normalized Scores; Higher values indicate better performance, except Energy Consumption and Life-Cycle Cost where higher scores indicate lower values / better performance)

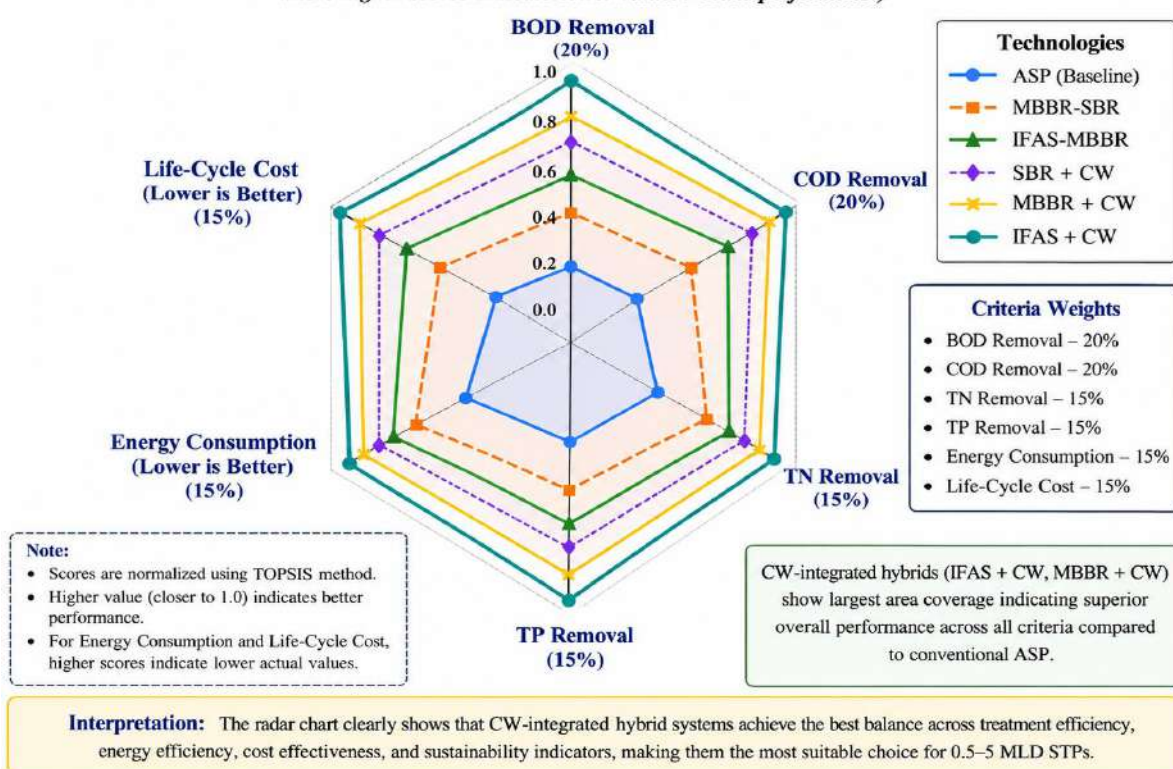


Figure 5: TOPSIS-based normalized performance comparison of the evaluated treatment technologies

Figure 5 shows the normalized multi-criteria performance of the six alternatives. IFAS + CW has the largest overall performance envelope, followed by MBBR + CW and IFAS-MBBR.

CW-integrated systems show lower modeled energy demand, carbon footprint and sludge generation, but require more land. IFAS + CW provides the strongest overall sustainability profile in the reported decision framework, while IFAS-MBBR remains preferable where land availability is highly constrained. Table 5 summarizes the sustainability indicators.

F. Recommended configuration

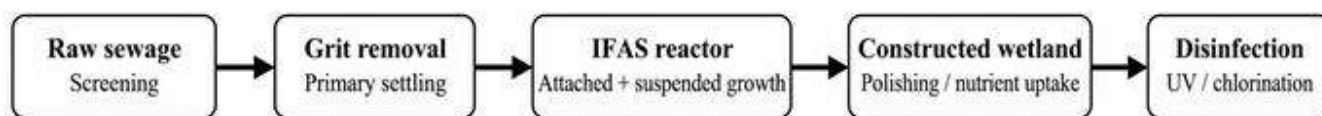


Figure 6: Recommended process configuration based on the TOPSIS result: IFAS + constructed wetland, followed by disinfection where required

The suggested process scheme is provided in Figure 6: raw sewage and screening vs. grit removal/primary settling vs. IFAS reactor vs. constructed wetland polishing vs. final disinfection (where necessary). Adaptation of the recommendation to site conditions should be carried out. IFAS-MBBR can be used more where land is the limiting factor, or costly, although its modeled energy demand is large. IFAS + CW has the most appropriate compromise in the chosen weights of MCDA, where land is available and sustainability is of priority.

V. LIMITATIONS

The research is a computer-based simulation and considers representative values of influent instead of a continuous full-scale monitoring data. Not all kinetic constants and calibration data, detailed discounted cash flows, and statistical validation measures are reported in the source manuscript. Consequently, the numbers can be used as relative design estimates. It is advisable to test out the full-scale application by field or pilot validation.

The ranking of the MCDA is based on the chosen criterion weights. The ranking can vary depending on various land prices, energy tariffs, effluent targets or institutional priorities. Specifically, the space demands of CW-integrated systems are higher, an aspect that can act as the nexus in tightly populated cities.

VI. CONCLUSION

This paper has compared six different treatment designs of decentralized STPs in the range of 0.5-5 MLD based on modeled pollutant elimination, energy consumption, cost-life-cycle and sustainability metrics. The best modeled BOD and COD removal was with IFAS-MBBR but CW-integrated systems tended to demand less energy and reduce modeled carbon removals and sludge production. Using TOPSIS criteria and weight adopted, IFAS + CW was able to rank first (CC = 0.912), then MBBR + CW (0.895), and IFAS-MBBR (0.868). The last suggestion is thus IFAS + CW with downstream disinfection where necessary to allow reuse. This outcome is conditional upon the specified assumptions and weights of criteria; land

Based strictly on the alternatives evaluated and the TOPSIS ranking, the optimized configuration is **IFAS + CW**. A practical process sequence is: screening → grit removal → primary settling → IFAS biological treatment → constructed-wetland polishing → final disinfection where reuse or regulatory requirements demand it. The disinfection step is a downstream treatment requirement and was not included as a separate TOPSIS alternative. The previously stated MBBR/IFAS → SBR → CW configuration has therefore been removed from the final recommendation because that exact configuration was not evaluated as a separate alternative in the study.

availability, energy cost, effluent requirement and operational adequacy should be taken into consideration and implemented on site.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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