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Optimization of nuclear solvents industrial effluent treatment using ferric-chloride precipitation and activated charcoal adsorption: A 4E parametric evaluation

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The Solvent Production Plant (SPP) at HWP Tuticorin generates hypersaline and organic contaminant effluents with elevated Chemical Oxygen Demand (COD) of 26,800 ppm, exceeding the regional Tamil Nadu Pollution Control Board (TNPCB) discharge limits at India. This study presents a comprehensive 4E (Environment, Energy, Exergy, Economics) parametric assessment of ferric chloride ($FeCl_3$) precipitation and activated charcoal adsorption for optimizing the treatment of solvent production effluents. The chemical based $FeCl_3$ precipitation method of treating effluent reduces COD to 9,650 ppm in single treatment but requires two to three successive precipitation cycles to achieve the Tamil Nadu Pollution Control Board (TNPCB) discharge standard. In contrast, fixed-bed activated charcoal adsorption reduces the COD by approximately 50%, while maintaining Total Dissolved Solids (TDS), generating no sludge, and allowing adsorbent regeneration using 0.3 M HCl, thereby improving process sustainability and economic performance. Based on the comparative 4E evaluation, a hybrid integrated treatment methodology is proposed in which activated charcoal adsorption is employed as a pre-treatment stage to reduce the initial organic load, followed by $FeCl_3$ precipitation as a polishing treatment to achieve the required discharge standards. This integrated approach reduces chemical consumption, sludge generation, energy demand, and overall operating costs while improving treatment efficiency. The Rotary Vacuum Drum Filter (RVDF) of $FeCl_3$ precipitation effectively separates ferric hydroxide sludge generated during the treatment process. The novelty of this work lies in the application of a 4E assessment framework to develop an integrated treatment strategy for hypersaline nuclear solvent effluents, providing a practical and sustainable solution for industrial effluent management.

Keywords: Activated charcoal, COD removal, 4-E parametric evaluation, Exergy, Nuclear solvents, Wastewater treatment

Introduction

The Solvent Production Plant (SPP), functioning inside the premises of Heavy Water Plant (HWP) Tuticorin and administered by the Heavy Water Board (HWB) a constituent Industrial unit of Department of Atomic Energy in Government of India, serves as a critical infrastructure in advancing India's closed nuclear fuel cycle. The facility is engaged in the synthesis of high-purity nuclear solvents, including Tributyl phosphate (TBP), Triisoamyl phosphate (TIAP), Trioctyl phosphine oxide (TOPO), Dihexyl octanamide (DHOA), and mono ester of di-2-ethylhexyl phosphonic acid (D_2EHPA-II). These solvents are indispensable in rare earth mineral partitioning and recovery processes implemented across key DAE institutions such as BARC, IGCAR, NFC[1,2]. They play a pivotal role in both the upstream and downstream segments of nuclear fuel reprocessing.

The SPP manufactures five major nuclear-grade solvents, each serving a specific function in nuclear fuel reprocessing and rare-earth extraction. TBP is extensively used for uranium and plutonium recovery through solvent extraction. TIAP serves as an alternative extractant to TBP in fast reactor fuel processing. TOPO is employed in solvent extraction during nuclear fuel reprocessing, while DHOA is used as a green solvent for actinide partitioning. D2EHPA-II is employed for the extraction and recovery of rare-earth elements, particularly thorium from monazite sand. These solvents constitute the principal products of the SPP and support India's nuclear fuel reprocessing and strategic rare-earth extraction programmes.

While producing these above solvents in indigenous form, it generates high-strength hypersaline effluents, primarily consisting of sodium chloride (NaCl), potassium chloride (KCl), and residual organic constituents. These contaminants result from hydrolysis reactions, alkali neutralization, and water wash streams during solvent purification processes[3]. A major environmental concern was the elevated chemical oxygen demand (COD), consistently measured around 26,800 ppm which is far exceeding the TNPCB's permissible limit of 250 ppm[4].

Unregulated discharge of such effluents leads to severe ecological repercussions, including oxygen depletion and aquatic toxicity[5]. Therefore, the development of a technically viable, energy-efficient, and economically sustainable effluent treatment system is imperative. The currently employed $FeCl_3$-based chemical precipitation method reduces COD to approximately 9650 ppm (Fig. 1). Although this represents a significant reduction in organic load, the treated effluent still exceeds TNPCB discharge limit of 250 ppm. Therefore, the existing industrial practise requires two to three successive $FeCl_3$ precipitation cycles, followed by sludge separation using a Rotary Vacuum Drum Filter (RVDF), before the treated effluent can meet the prescribed discharge standards. However, these repeated treatment cycles result in significant ferric hydroxide sludge generation (320 – 560 kg/m^3), increased TDS, higher chemical consumption, greater energy demand, longer treatment time, and elevated operational costs[6]. These limitations motivated the present study to investigate activated charcoal adsorption as a pre-treatment step to reduce the initial organic load and thereby decrease the number of precipitation cycles required to achieve regulatory compliance.

This study explores fixed-bed charcoal adsorption as a sustainable, cost-effective method, achieving ~50% COD reduction (~13,600 ppm). In comparison the $FeCl_3$ precipitation method shows better COD/TOC removal but increased TDS due to dissolved ions, large quantity of sludge generation by neutralizing the charges of suspended particles forming a clump together to form large particles (flocs), high energy consumption from different complex treatment processes involves mechanical, hydraulic and electrical components, incursion of chemical expenditures makes it unattractive for sustainable and energy efficient effluent treatment.

Although activated charcoal adsorption effectively reduces the COD by approximately 50%, the treated effluent still continued about 13,600 ppm COD, which is significantly higher than the TNPCB discharge limit of 250 ppm. Achieving the prescribed discharge standard using activated charcoal adsorption alone would require several adsorption columns connected in parallel configured series, frequent regeneration of the adsorbent, increased hydraulic retention time, larger installation space, and higher maintenance requirements. Such a multi-stage adsorption system would substantially increase capital investment, operational complexity, and downtime associated with charcoal regeneration, making it impractical for continuous industrial scale operation at the solvent production plant. However, the spent charcoal was successfully regenerated using 3% HCl, enabling reuse of the filtration bed and reducing solid waste generation. Therefore, activated charcoal is considered more suitable as a pre-treatment stage for reducing the initial organic load before $FeCl_3$ precipitation rather than as a standalone treatment process. The activated charcoal treatment demonstrated effective adsorption of organic contaminants in numerous industrial wastewater treatment applications[7,8].

The novelty of this real time research work lies in the advanced method of using 4E (Environment, Energy, Exergy, Economics) parametric analysis in treatment of nuclear solvent effluents of Atomic

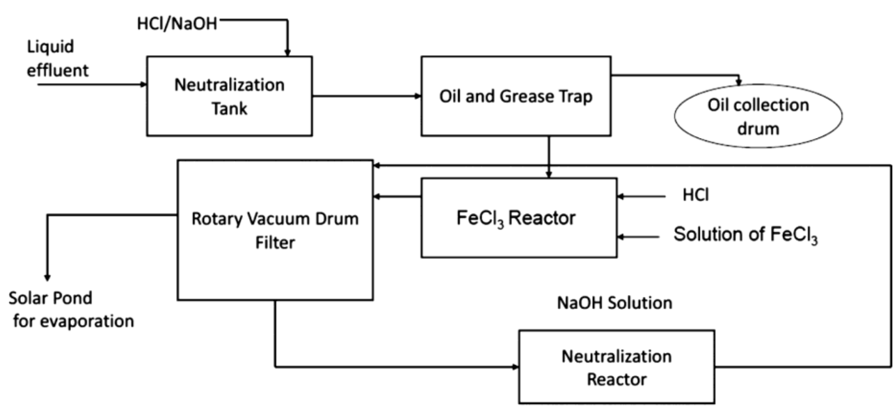

Fig. 1 — Industrial based $FeCl_3$ precipitation method at SPP unit of HWP Tuticorin

Energy Industry rarely documented in literatures. A detailed 4E (Environment, Energy, Exergy, Economics) evaluation underscores that activated charcoal outperforms $FeCl_3$ precipitation in terms of energy, exergy efficiencies and cost-effectiveness which clearly indicates the efficacy of activated charcoal in pre-treatment technology options of treating the nuclear solvent effluents through a simple hybrid integrated effluent treatment system with a priority of zero liquid discharge.

Experimental Section

Effluent sampling and characterization

Industrial effluent samples were collected from the SPP of Heavy Water Plant (HWP) Tuticorin, during routine solvent production operations. The effluent primarily consisted of hypersaline wastewater containing high concentrations of sodium chloride (NaCl), potassium chloride (KCl), dissolved organic compounds, and suspended solids. The collected samples were thoroughly mixed and stored in clean polyethylene containers prior to analysis. The initial physicochemical characteristics, including chemical oxygen demand (COD), total organic carbon (TOC), total dissolved solids (TDS), and pH, were determined following standard analytical procedures. The analytical instruments used and the corresponding TNPCB discharge limits are presented in Table 1.

Analytical methods

The physicochemical properties of the raw and treated effluents were analysed using standard laboratory procedures. COD was determined using the closed reflux dichromate method, TOC was measured using a TOC analyser, TDS was determined using a conductivity-based method, and pH was measured using a calibrated digital pH meter. The analytical methods, instruments employed, and TNPCB discharge standards are summarized in Table 1.

Ferric chloride precipitation

Ferric chloride ($FeCl_3$) precipitation was employed as the conventional treatment method for removing organic contaminants and suspended solids from the industrial effluent. Ferric chloride was added to the wastewater under controlled mixing conditions, where it underwent hydrolysis to form amorphous ferric hydroxide [$Fe(OH)_3$] flocs. These flocs removed suspended particles and dissolved organic matter through charge neutralization, adsorption, and sweep flocculation mechanisms. The generated sludge was subsequently separated using a Rotary Vacuum Drum Filter (RVDF), and treated effluent was analysed for COD, TOC, TDS, and pH.

Activated charcoal adsorption

Activated charcoal adsorption experiments were carried out using a fixed bed adsorption column to evaluate the removal of dissolved organic contaminants from the industrial effluent. The wastewater was continuously passed through the activated charcoal bed under controlled flow conditions. The treated effluent was analysed for COD, TOC, TDS, and pH to assess adsorption performance. After adsorption, the exhausted activated charcoal was regenerated using 3% hydrochloric acid (HCl), washed with deionized water, and reused in subsequent treatment cycles to evaluate its regeneration efficiency and sustainability.

Comparative 4E assessment

The performance of ferric chloride precipitation and activated charcoal adsorption were comparatively evaluated using the 4E framework comprising Environmental, Energy, Exergy, and Economic analyses. Environmental performance was assessed

Table 1 — Analytical parameters, instrumentation, working range, and TNPCB limits

Parameter	Instrument / Method	Working range	TNPCB limit
Density (g/cc)	Mettler Toledo weighing balance	0.0001 g to 180 g	Not applicable
pH	LABINDIA PICO+ pH meter	1 – 14	6.5 – 8.5
Conductivity (mS/cm)	LABINDIA PICO+ conductivity meter	0.001 μS/cm – 100 mS/cm	Not specifies (monitoring parameter)
TDS (ppm)	Gravimetric (evaporation) method	0 – 50,000 ppm	2100 ppm
Sodium Ion (Na^+)	Flame photometry (ELICO)	0 – 100 ppm	Not specified (monitoring parameter)
Potassium Ion (K^+)	Flame photometry (ELICO)	0 – 100 ppm	Not specified (monitoring parameter)
Chloride ion (Cl^-)	Argentometric titration	150 – 10,000 mg/L (0.015% – 1.0%)	0.06%
COD (ppm)	Redox titration ($K_2Cr_2O_7$ Method)	50 – 800 ppm (direct) / Up to 40,000 ppm with dilution	< 250 ppm

based on COD, TOC, TDS, and sludge generation. Energy and exergy analyses considered the overall energy consumption and thermodynamic efficiency of each treatment process. Economic evaluation included chemical consumption, operating costs, regeneration requirements, and waste management expenses. The comparative assessment was used to identify the most sustainable treatment strategy and to propose an integrated hybrid treatment process for industrial effluent management.

Treatment methodology

The current effluent treatment strategy combines $FeCl_3$ chemical precipitation and activated charcoal adsorption to enhance contaminant removal from hypersaline effluents of the SPP. $FeCl_3$ precipitation operates on the principle of hydrolysis, forming insoluble ferric hydroxide [$Fe(OH)_3$] flocs that coagulate and settle organic and suspended impurities (Fig. 2). The freshly formed $Fe(OH)_3$ flocs possess a large surface area and a positive surface charge, which destabilize negatively charged colloidal particles through charge neutralization. In addition, dissolved organic contaminants are adsorbed onto the floc surfaces, while suspended solids are removed by sweep flocculation, where the growing hydroxide precipitates physically entrap fine particles and organic matter within the floc matrix. As the flocs increase in size and density, they readily settle under gravity, enabling efficient separation by the rotary vacuum drum filter (RVDF). Activated charcoal adsorption, leveraging its hierarchical pore structure and extensive surface area (500 to 1500 m²/g), removes residual organic contaminants. The fixed-bed charcoal column (60 cm × 2.5 cm) treats effluent batches through combined screening and adsorption mechanisms (Fig. 3). A comparative analysis of both methods highlights the efficiency of chemical precipitation in removing suspended solids and a significant fraction of organic contaminants, whereas activated charcoal adsorption provides effective polishing of the remaining dissolved organic matter, thereby supporting the development of an optimized sequential treatment process for the SPP effluent at HWP Tuticorin.

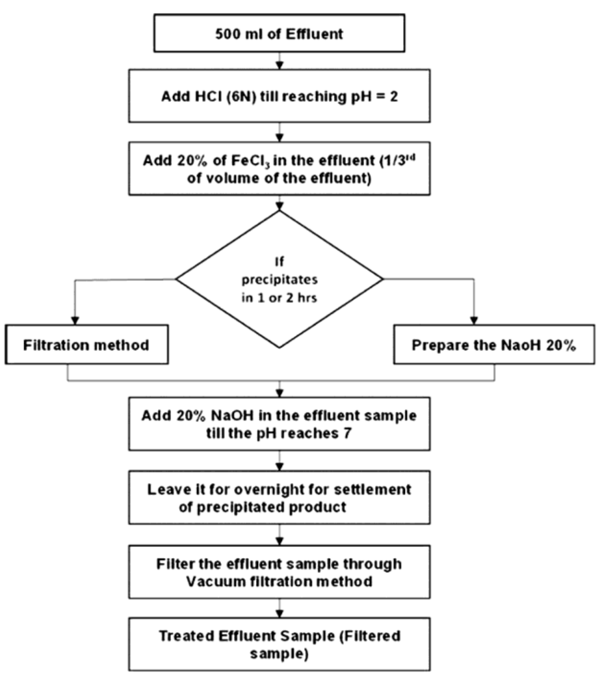

Fig. 2 — Flowchart for $FeCl_3$ precipitation process

Results and Discussion

Environmental analysis

The raw effluent from the SPP exhibited high organic contamination, with a COD concentration of 26,800 ppm and elevated (TOC of 6700 ppm. The effluent was also characterized by a TDS concentration of 28,681 ppm and an alkaline pH of 8.5–9.0, exceeding the TNPCB discharge limits. The data presented in Table 2 emphasize the urgent need for effective effluent treatment strategies to ensure regulatory compliance and environmental safety.

$FeCl_3$ precipitation

$FeCl_3$ treatment functions primarily through coagulation and precipitation[9]. Upon dosing, ferric chloride hydrolyzes in water forming ferric hydroxide [$Fe(OH)_3$] flocs, which effectively adsorb and enmesh

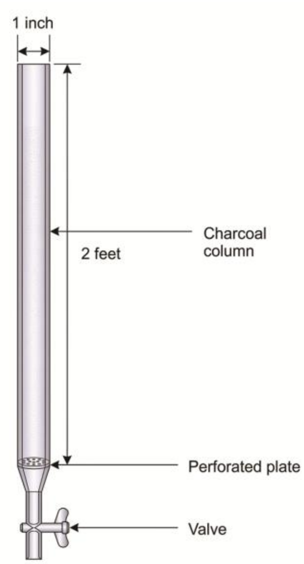

Fig. 3 — Charcoal adsorption process through charcoal column

suspended solids and organic contaminants, leading to their removal via sedimentation. The hydrolysis reaction can be represented as:

$$FeCl_3+3H_2O \rightarrow Fe(OH)_3(s)+3HCl$$

This mechanism results in significant reduction of organic pollutants, evident from the Table 3 as COD drops from 26,800 ppm to 9650 ppm. Correspondingly, TOC decreases, confirming effective organic removal. The superior performance of ferric chloride precipitation can be attributed to the physicochemical properties of the ferric hydroxide [$Fe(OH)_3$] flocs formed during hydrolysis. Ferric hydroxide is preferred as a coagulant because it forms amorphous flocs with a large specific surface area and an abundant active adsorption sites. These flocs exhibit a strong affinity towards dissolved organic compounds, particularly polar organic molecules and organophosphorus species present in solvent production effluents. The contaminants are removed through a combination of charge neutralization, adsorption onto the $Fe(OH)_3$ surface, and sweep flocculation, in which the precipitating hydroxide physically entraps suspended solids and dissolved organic matter. The mechanisms collectively contribute to the substantial reduction in COD and TOC observed after $FeCl_3$ treatment. TDS increases after $FeCl_3$ treatment because $FeCl_3$ dissociates in water and Fe^{3+} forms $Fe(OH)_3$, while the addition of NaOH during pH adjustment increases the concentration of dissolved sodium salts, thereby increasing the TDS despite the reduction in organic pollutants[10,11].

Charcoal adsorption

Activated charcoal adsorption effectively reduced the COD concentration (Table 4) by about 50%, lowering it from a high organic load of 28600 ppm to approximately 13,600 ppm. The treatment primarily relies on physical adsorption, with organics captured in the porous structure of the charcoal, resulting in a proportional decrease in total organic carbon[12]. The process maintained near-neutral pH and caused negligible change in TDS, indicating minimal salt loading[13].

Importantly, regeneration studies demonstrated that the charcoal bed could be effectively restored using a 3% HCl solution. This regeneration not only recovered the adsorption capacity but also minimized solid waste generation, highlighting the sustainability and cyclic reusability of the charcoal adsorbent[14]. Such successful regeneration supports the long-term feasibility of charcoal-based effluent treatment by reducing operational costs and environmental impacts[15].

Statistical evaluation of organic load reduction charcoal adsorption treatment

Linear regression analysis demonstrates that both $FeCl_3$ coagulation and charcoal adsorption exhibit strong correlations ($R^2 > 0.8$) with reductions in COD and TOC, confirming their efficacy in organic pollutant removal (Fig. 4a). Such correlation-based evaluations are widely used to assess the predictive strength of treatment methods for key water quality parameters[16]. A 500 mL of SPP effluent sample with a COD concentration of 26,800 mg/L contains a total COD load of 26.8 g/L oxidizable organic matter. In contrast, charcoal adsorption maintains stable level of ionic level, preserving the ionic balance without increasing the salt content (Table 4). Therefore, both treatments effectively reduce organic load but charcoal adsorption offers superior sustainability in restricting the increase of salt loading by maintaining the TDS level in mg/L (ppm) same as feed quality and maintaining water quality integrity by effectively reduces the COD to 50% and TOC to ~34% (Fig. 4b).

Energy analysis

$FeCl_3$ precipitation requires significant energy input for pumping raw effluent, chemical dosing, pH

Table 2 — Feed effluent characteristics of SPP of HWP Tuticorin

Effluent Type from solvent synthesis	ρ (g/cc)	pH	K (mS/cm)	TDS (ppm)	Na^+ (%)	K^+ (%)	Cl^- (%)	COD (ppm)
TBP, TIAP, TOPO, DHOA, D2EPHA-II	1.037	8.7	43	28,681	0.98	1.66	1.5	26,800

Table 3 — Effluent characteristics after $FeCl_3$ precipitation treatment

Effluent Type from Solvent Synthesis	Density (g/cc)	pH	Conductivity K (mS/cm)	TDS (ppm)	Na^+ (%)	K^+ (%)	Cl^- (%)	COD (ppm)
TBP, TIAP, TOPO, DHOA, D2EPHA-II	1.030	6.8	108	72,360	3.1	3.2	4.2	9650

Table 4 — Effluent characteristics after charcoal adsorption effluent treatment

Parameter	Density (g/cc)	pH	Conductivity K (mS/cm)	TDS (ppm)	Na^+ (%)	K^+ (%)	Cl^- (%)	COD (ppm)
Effluent Mixture	1.0085	8.09	44.71	28,020	0.91	1.60	1.48	13,600

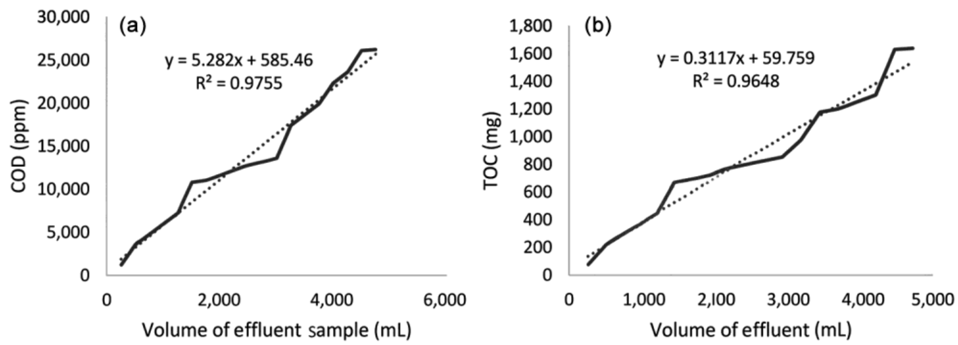

Fig. 4 — (a) COD and (b) TOC analysis curves for activated charcoal adsorption

Table 5 — Comprehensive pump systems used in $FeCl_3$ effluent treatment method for energy requirements

Pump Type	Quantity (Nos)	Flow rate (Q)	Head (H)	Input power (Total)	Function
Peristaltic pump (raw effluent transfer)	2	20 L/min	5 meter	23 W	For transferring effluent before or during treatment
Chemical metering pump	2	2 L/h	10–20 meters	25 W	Precise dosing of $FeCl_3$, pH adjusters, or additives
Vacuum pump (filtration method)	1	20 L/min	10 meter	50 W	For vacuum-assisted filtration of partially treated effluent
Peristaltic pump (treated water transfer)	1	20 L/min	5 meter	23 W	Transfers final effluent to holding tank or discharge

Table 6 — Comprehensive pump systems used in charcoal adsorption effluent treatment method for energy requirements

Pump purpose	Quantity (No.)	Flow rate (Q)	Head (H)	Input power (Total)	Function
Feed pump to charcoal column	1	20 L/min	8 meter	23 W	Transfers pretreated effluent to charcoal column
Treated effluent transfer pump	1	20 L/min	5 meter	23 W	Moves adsorbed (clean) water to collection/storage tank

adjustment, vacuum assisted filtration and treated effluent transfer as shown in Table 5. Conversely, charcoal adsorption consumes less energy, mainly for pumping and periodic acid regeneration, resulting in 30-40% lower energy consumption as shown in Table 6.

The consolidated pump performance graphs demonstrate the relationship between flow rate and key operational metric such as head, input power, hydraulic power, and efficiency across different pump types used in effluent treatment (Fig. 5). Each pump exhibits a distinct Best Efficiency Point (BEP), indicating the optimal flow rate for maximum energy conversion efficiency (Fig. 5). The BEP is critical design and operational benchmark in fluid systems engineering and energy optimization[17].

From an energy analysis standpoint, input power generally increases with flow rate, but not always proportionally to hydraulic power, causing energy inefficiencies beyond the BEP range. Operating each pump near its BEP ensures that a higher percentage of input energy is effectively converted into hydraulic output, thereby optimizing energy consumption and enhancing overall system performance and sustainability.

Based on the pump performance curves and energy efficiency analysis, each pump in the effluent treatment system performs most efficiently at its Best Efficiency Point (BEP), where the conversion of input electrical energy to hydraulic power is maximized[18]. The overall energy efficiency of the system is determined by the product of pump, motor, and drive efficiencies, expressed as follows[19]:

$$\eta_{energy}=\eta_{pump}\times\eta_{motor}\times\eta_{drive}$$

Peristaltic pumps, vacuum pumps and chemical metering pumps demonstrate BEP efficiencies in the range of 60% to 70%, In the $FeCl_3$ precipitation method, the energy consumption is relatively high due to the inclusion of the vacuum pump, despite efficient chemical dosing. The total input power is approximately ~100 W, with an average system efficiency of 44.2% with motor and drive efficiency of around 85%.

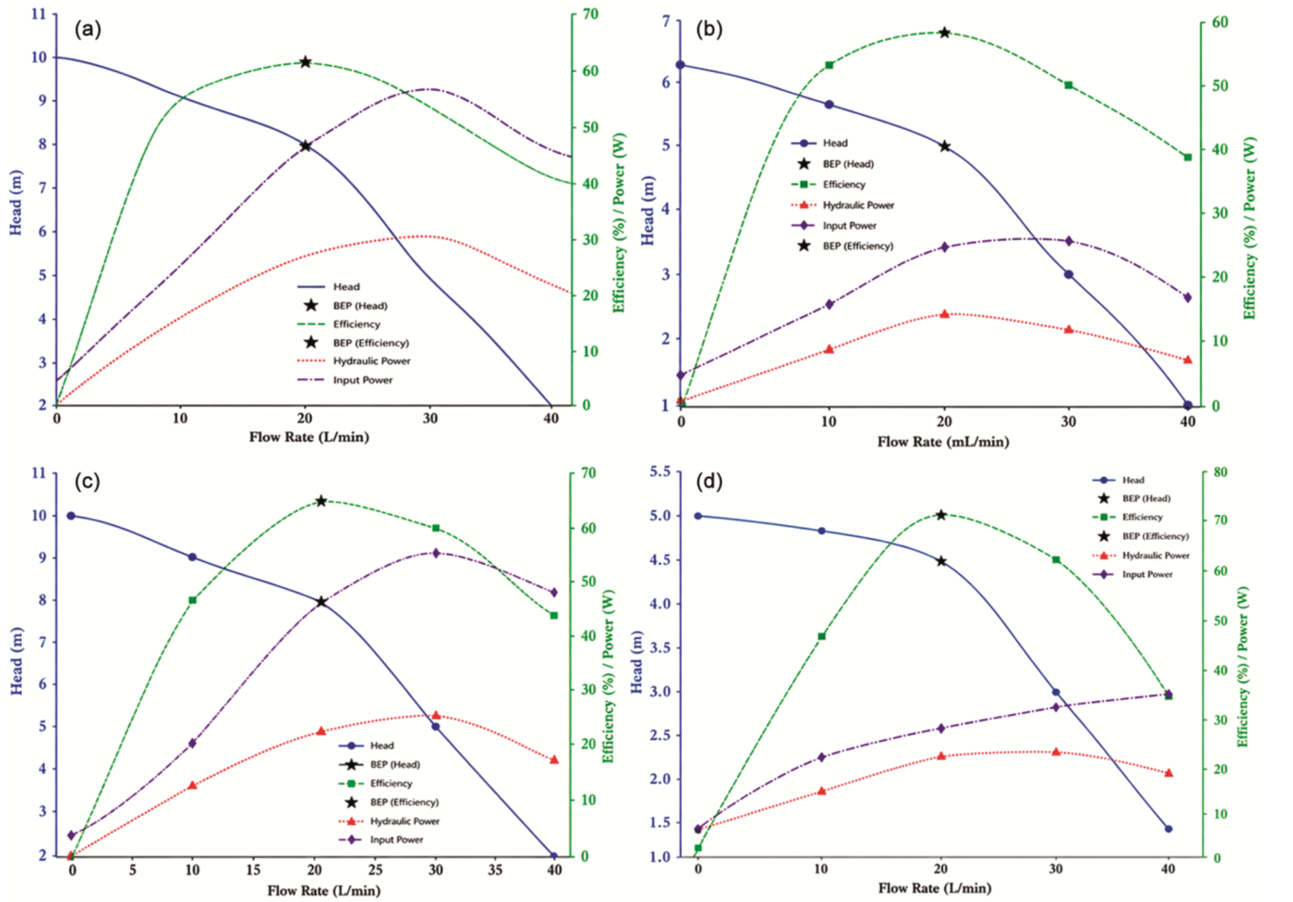

Fig. 5 — (a) Peristaltic pump, (b) chemical metering pump, (c) vacuum pump and (d) treated water transfer pump performance curves with BEP

In contrast, the charcoal adsorption method uses two low-head peristaltic pumps with a combined input power of only ~46 W and a similar average efficiency of 51.9 % resulting in a more energy-sustainable operation. Therefore, operating all pumps near their BEP and maintaining high motor and drive efficiency are essential to improving overall energy performance. The charcoal-based systems achieves an energy economy of 2.30 W/(L/min) compared to 6.05 W(L/min) for the $FeCl_3$ precipitation method which is approximately 62% lowerto making it more suitable for continuous energy efficient effluent treatment options.

Exergy analysis

Exergy analysis of pumps in effluent treatment systems provides a measure of how effectively the input energy is converted into useful hydraulic work, allowing identification of irreversibility and performance losses across different treatment configurations[19,20].

The higher exergy destruction in the $FeCl_3$ precipitation method (Table 7) is primarily due to the operation of vacuum and chemical metering pumps, which contribute significant irreversibilities owing to high head requirements and non-ideal energy utilization[21]. The exergy destruction rate in such components can be expressed as:

$$\dot{E}_D = \dot{W}\ input - \dot{E}\ useful$$

In contrast, the charcoal adsorption system uses low-head peristaltic pumps operating near their BEP, leading to reduced irreversibilities and lower exergy losses. The specific exergy of the working fluid is defined as:

$$e = (h- h_0) - T_0\,(s - s_0)$$

where h and s are the specific enthalpy and entropy, and T_0, h_0, and s_0 are the environmental reference values[22]. The exergy efficiency of the pump is then given by:

Table 7 — Exergy analysis of $FeCl_3$ and Charcoal based effluent treatment method

Method	Pump type	Quantity (Nos.)	Exergy destruction rate (W)	Exergy efficiency (%)
	Peristaltic pump (raw effluent transfer)	2	6.5	60
$FeCl_3$ precipitation method	Chemical metering pump	2	12.5	50
	Vacuum pump (filtration)	1	29.5	41
	Peristaltic pump (treated water transfer)	1	6.7	60
	$FeCl_3$ effluent treatment total		55.2 W	51.2%
Charcoal adsorption	Feed pump to charcoal column	1	5.5	62
	Treated effluent transfer pump (charcoal)	1	6.6	61
	Charcoal adsorption effluent treatment total		12.1 W	50.6%

Table 8 — Comparative economic analysis of $FeCl_3$ precipitation and charcoal adsorption effluent treatment method

Criteria	$FeCl_3$ Precipitation	Charcoal Adsorption
Capital cost	Rs.18,000 to Rs.25,000	Rs.15,000 to Rs.22,000
Operating cost	Rs.160 to Rs.310 per 100 L batch	Rs.65 to Rs.100 per 100 L batch
Maintenance cost	Rs.2,000 to Rs.3,000 per year	Rs.400 to Rs.500 per year
System lifetime	20 years	20 years
Scale flexibility	Suitable	Suitable but needs larger space for chain of operations
Waste generation & reusability	Enormous solid waste & non reusable	No solid waste but reusable the bed after regeneration

$$\eta_{ex} = \frac{\dot{E}\ useful}{W\ input}$$

Higher exergy efficiency in such systems indicates better utilization of input energy for useful work, making it a critical parameter for evaluating and optimizing the thermodynamic performance of effluent treatment processes[23].

Economic analysis

An economic analysis is essential for evaluating the feasibility and long-term viability of effluent treatment technologies, especially when selecting between alternative methods such as $FeCl_3$ precipitation and charcoal adsorption[24]. It provides a quantitative basis for comparing capital investment, operational expenses, maintenance requirements, and sustainability considerations.

By assessing these economic parameters, decision-makers can identify the most cost-effective and scalable solution that aligns with technical performance and environmental goals[25]. Table 8 presents a comparative economic overview of both systems at the lab scale of handling flow rate 20 L/min.

Conclusion

A comprehensive 4E assessment was carried out to evaluate ferric chloride ($FeCl_3$) precipitation and activated charcoal adsorption for the treatment of organic-rich hypersaline effluents generated from the Solvent Production Plant of HWP Tuticorin. $FeCl_3$ precipitation achieved a higher COD reduction from 28,600 ppm to approximately 9,650 ppm (≈64%) but required two to three successive treatment cycles to comply with the Tamil Nadu Pollution Control Board (TNPCB) discharge limit of 250 ppm. However, the process resulted in increased Total Dissolved Solids (TDS), substantial ferric hydroxide sludge generation, higher chemical consumption, and greater energy and exergy losses associated with chemical dosing and vacuum filtration. Activated charcoal adsorption reduced the COD by approximately 50% to around 13,600 ppm while maintaining stable TDS concentration of 28,020 ppm, near neutral pH, and no sludge generation. The adsorbent could be effectively regenerated using 3% HCl, making the process more sustainable, energy efficient, and economically attractive. Although activated charcoal adsorption alone was insufficient to meet the TNPCB discharge standards, it significantly reduced the initial organic load without increasing the dissolved salt concentration. Based on the comparative 4E assessment, an integrated hybrid treatment methodology is proposed in which activated charcoal adsorption is employed as a pre-treatment stage, followed by $FeCl_3$ precipitation as the polishing treatment. This integrated approach reduces the organic load entering the chemical treatment stage, thereby decreasing number of $FeCl_3$ precipitation cycles required, reducing chemical consumption, sludge generation, energy demand, and overall operating costs while improving compliance with TNPCB discharge standards. The proposed treatment strategy provides a practical and sustainable solution for the management of hypersaline solvent organic rich effluents of nuclear solvent production plants and also offers a framework for similar industrial wastewater treatment applications.

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Conflict of Interest

The authors declare no conflict of interest.

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