Supplementary Information (SI) for Environmental Science: Water Research & Technology.

Techno-economic and Life cycle assessment of an integrated Electrocoagulation process for sustainable treatment of arsenic and fluoride contaminated groundwater

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Supplementary materials

S1. Electrocoagulation water treatment

In the electrocoagulation process, the coagulant was generated in situ by electro-dissolution of the aluminium electrode. Thus, it does not require any chemical addition. The polymeric compounds of aluminium hydroxide remove the arsenic and fluoride through coagulation, adsorption and charge neutralisation mechanisms. The effluent from the electrocoagulation reactor was sent to the sedimentation tank, from where 80 % of the total feed was collected as supernatant treated water, while 20% was in the form of slurry, which was collected from the bottom and filtered into the sludge dewatering unit (filter press). The sludge cake generated in the filter press was sun-dried and sent for its sustainable management.

The major management practices for sludge are immobilisation of sludge in bricks and composites, as well as utilisation as a catalyst support. The LCA of the laboratory-scale electrocoagulation process with sludge management as immobilisation in clay bricks has already been published in the authors' earlier work (Goyal & Mondal, 2022a). The present study focuses on the LCA with the impact of electrocoagulation reactor sizes and a detailed techno-economic assessment of the complete process. Thus, the sludge management has been excluded from the present work.

The details of scale-up set-ups are obtained from the Indian patent IN 202311014986. The amount of aluminium dissolved in the EC reactor during the treatment process is evaluated using Faraday's law (equation S1). The energy consumed in the process is evaluated by equation S2. Sodium chloride (NaCl) was used to enhance the conductivity of the water. In the real field (R_5), the contaminated water has more TDS and conductivity, thus less sodium chloride is required for the electrocoagulation process. The operating conditions and details of each setup are presented in Table **.

$$C_{Al} = \frac{MIt}{zFV_R} \qquad \text{S1}$$

$$E = \frac{I \times V \times t \times V_w \times 3.6}{V_R \times 60 \times 1000} MJ \qquad \text{S2}$$

Here C_{Al} is the amount of aluminum dissolves per liter of solution, M is the atomic weight of electrode material (for aluminum M= 26.98 g/mol), I is current supplied (in Ampere), t is the residence time (in seconds), z is charge (For Al = 3), F is faraday's constant (F=96485), V_R is the volume of reactor in liter, V_w is the volume of water to be treated, E is energy consumes in MJ and V is the voltage (in volts).

Table S1 Details of EC reactors, electrodes and operating conditions of the treatment process

Characteristics/ conditions	**R-1 1.8 L**	**R-2 20 L**	**R-3 100 L**	**R-4 650 L**	**R-5 1200 L**
Electrocoagulation reactor					
Material	Perplex	Perplex	Perplex	Multilayer plastic	Multilayer plastic
Dimension(s)	15×10×12 cm^3	40×20×25 cm^3	60×40×50 cm^3	D=100 cm, H=71 cm	D= 120 cm, H= 110 cm
Working Volume	1.4 L	18 L	80 L	550 L	1000 L
Type	Up-flow	Up-flow	Up-flow	Up-flow	Up-flow
Electrodes					
No. of electrodes	4	12	16	28	40
Shape	Rectangular	Rectangular	Rectangular	Rectangular	Rectangular
Dimensions	8 cm ×8 cm	14 cm ×20 cm	30 cm ×30 cm	50 cm × 60 cm	50 cm × 60 cm
Total Area	0.0512 m^2	0.672 m^2	2.9 m^2	16.8 m^2	24 m^2
Plate arrangement	Parallel	Parallel	Parallel	Parallel	Parallel
Electrode gap	1 cm	1 cm	1 cm	1 cm	1 cm
Operating conditions					
pH	7.0	7.0	7.0	7.0	6-7

Residence time	95 min	95 min	90 min	85 min	60 min
Current density	~10 A/m^2	~10 A/m^2	~10 A/m^2	~10 A/m^2	6.25 A/m^2
Voltage	5-5.5 V	2.5-3.5 V	2.2-2.4	3-4 V	6.5-7 V
Stirring					
Stirrer/pump	3 W stirrer	18 W (1 No.)	18 W (2 No.)	18 W (4 No.)	45 W (4 No.)

Operational constraints of field-scale operation

In the field-scale electrocoagulation system, certain operational constraints were observed. The performance of the process is highly dependent on parameters such as pH, conductivity, electrode spacing, and current density, which require careful monitoring and control to ensure stable operation. Electrode passivation and wear over time may reduce treatment efficiency and necessitate periodic cleaning or replacement, thereby influencing long-term sustainability. Additionally, uninterrupted power supply and timely sludge withdrawal from the sedimentation unit are essential to avoid operational bottlenecks. These constraints highlight the importance of proper monitoring and maintenance protocols in real-field applications.

S2 Life cycle inventory

Figure S1 shows the system boundary of the treatment process. The materials and energy input to the treatment process are presented in the life cycle inventory Table S2 for different plant capacity scenarios.

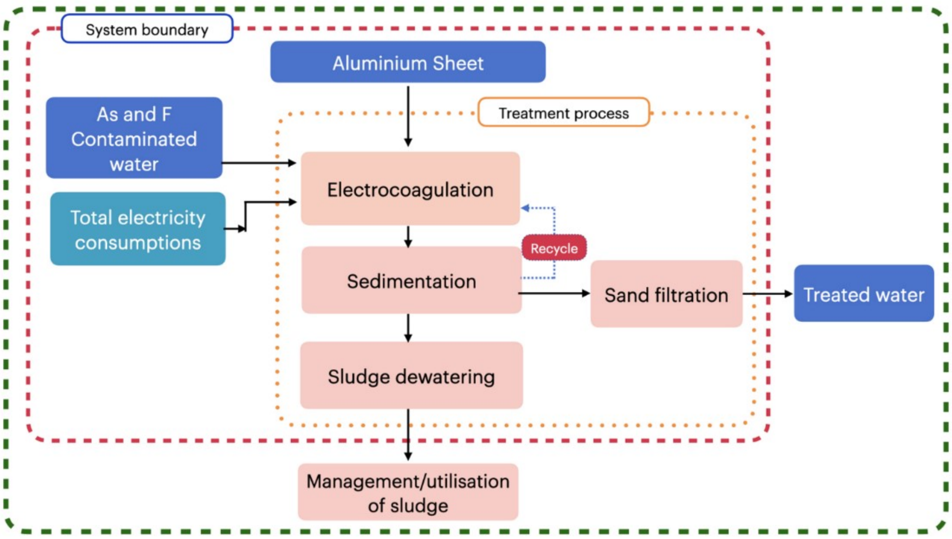

Figure S1 System boundary of the integrated treatment process for the LCA study

Table S2 Life cycle inventory for EC based different plant capacity treatment

	R_1	**R_2**	**R_3**	**R_4**	**R_5**
Inputs					
As and F contaminated water	1.01 m^3	1.01 m^3	1.01 m^3	1.01 m^3	1.01 m^3
Diesel mix at refinery (Al electrode transportation)	0.00137 kg	0.00137 kg	0.00134 kg	0.0011 kg	0.000531 kg
Al Electrode (Aluminium sheet)	0.194 kg	0.194 kg	0.189 kg	0.155 kg	0.075 kg
Electricity grid mix (electrochemical reaction)	11.04 MJ	6.3 MJ	4.4 MJ	6.1 MJ	3.8 MJ
Electricity grid mix (stirring/mixing)	12.45 MJ	5.81 MJ	2.56 MJ	0.67 MJ	0.445 MJ
Electricity grid mix (filtration)	-	-	-	-	1.2 MJ
Sodium chloride	0.5 kg	0.5 kg	0.5 kg	0.5 kg	0.15 kg
Outputs					
Treated water	1 m^3	1 m^3	1 m^3	1 m^3	1 m^3
Arsenic	-0.54 g	-0.54 g	-0.54 g	-0.54 g	-0.64 g
Fluoride	-4.5 g	-4.5 g	-4.5 g	-4.5 g	-

Sample calculations

(1) Aluminium electrode consumptions

For R_1, Current density j: 10 A/m^2; Residence time RT: 95 min = 95*60 sec; Electrode area A: 0.0512 m^2

Reactor volume V_R = 1.4 L, Volume of water to be treated: V_w = 1000 L

Aluminium dissolutions using Faraday's law

$$Al_{R_1} = \left(\frac{MIt}{zFV_R}\right) \times V_w = \left(\frac{M(j.A)t}{zFV_R}\right) \times V_w = \left(\frac{26.98 \times 10 \times 0.0512 \times 95 \times 60 \times 1000}{3 \times 96485 \times 1.4}\right) = 194\,\frac{g}{L}$$

For R_2, Current density j: 10 A/m^2; Residence time RT: 95 min = 95*60 sec; Electrode area A: 0.672 m^2

Reactor volume V_R = 18 L, Volume of water to be treated: V_w = 1000 L

Aluminium dissolutions using Faraday's law

$$Al_{R_1} = \left(\frac{MIt}{zFV_R}\right) \times V_w = \left(\frac{M(j.A)t}{zFV_R}\right) \times V_w = \left(\frac{26.98 \times 9.9 \times 0.67 \times 95 \times 60 \times 1000}{3 \times 96485 \times 18}\right) = 194\,\frac{g}{L}$$

For R_3, Current density j: ~10 A/m^2; Residence time RT: 90 min = 90*60 sec; Electrode area A: 2.8 m^2

Reactor volume V_R = 80 L, Volume of water to be treated: V_w = 1000 L

Aluminium dissolutions using Faraday's law

$$Al_{R_1} = \left(\frac{MIt}{zFV_R}\right) \times V_w = \left(\frac{M(j.A)t}{zFV_R}\right) \times V_w = \left(\frac{26.98 \times 10.35 \times 2.9 \times 90 \times 60 \times 1000}{3 \times 96485 \times 80}\right) = 189\,\frac{g}{L}$$

For R_4, Current density j: ~10 A/m^2; Residence time RT: 85 min = 85*60 sec; Electrode area A: 16.8 m^2

Reactor volume V_R = 550 L, Volume of water to be treated: V_w = 1000 L

Aluminium dissolutions using Faraday's law

$$Al_{R_1} = \left(\frac{MIt}{zFV_R}\right) \times V_w = \left(\frac{M(j.A)t}{zFV_R}\right) \times V_w = \left(\frac{26.98 \times 10.7 \times 16.8 \times 85 \times 60 \times 1000}{3 \times 96485 \times 550}\right) = 155\,\frac{g}{L}$$

For R_4, Current density j: 6.25 A/m^2; Residence time RT: 60 min = 60*60 sec; Electrode area A: 24 m^2

Reactor volume V_R = 1000 L, Volume of water to be treated: V_w = 1000 L

Aluminium dissolutions using Faraday's law

$$Al_{R_1} = \left(\frac{MIt}{zFV_R}\right) \times V_w = \left(\frac{M(j.A)t}{zFV_R}\right) \times V_w = 1.5 \times \left(\frac{26.98 \times 6.25 \times 24 \times 60 \times 60 \times 1000}{3 \times 96485 \times 1000}\right) = 75\,\frac{g}{L}$$

(2) Electricity consumption in electrochemical treatment

For R_1, Current: 0.512 A, V: 5.3 V

$$E = \frac{I \times V \times RT \times V_w \times 3.6}{V_R \times 60 \times 1000} MJ = \frac{0.512 \times 5.3 \times 95 \times 1000 \times 3.6}{1.4 \times 60 \times 1000} = 11.04\ MJ$$

For R_2, Current: 6.65 A, V: 3 V

$$E = \frac{6.65 \times 3 \times 95 \times 1000 \times 3.6}{18 \times 60 \times 1000} = 6.3\ MJ$$

For R_3, Current: 30 A, V: 2.2 V

$$E = \frac{30 \times 2.2 \times 90 \times 1000 \times 3.6}{80 \times 60 \times 1000} = 4.45\ MJ$$

For R_4, Current: 180 A, V: 3.6 V

$$E = \frac{180 \times 3.6 \times 85 \times 1000 \times 3.6}{550 \times 60 \times 1000} = 6.0\ MJ$$

For R_5, Current: 150 A, V: 6.5 V

$$E = \frac{150 \times 7.0 \times 60 \times 1000 \times 3.6}{1000 \times 60 \times 1000} = 3.8\ MJ$$

S3 Life cycle impact assessment methodology

The ReCiPe 2016 midpoint (H) method has been used for the assessment of impacts under the 18 different categories. The 18 different impact categories with their abbreviation and units are as follows: Global warming potential (GWP, kg CO2 eq.), Terrestrial acidification (TAP, kg SO2 eq.), Particulate matter formation potential (PMFP, kg PM2.5 eq., Ozone depletion potential (ODP, kg CFC-11 eq.), Freshwater consumption potential (FCP, m^3), Land use (LUP, Annual crop eq. y), Fossil depletion potential (FDP, kg oil eq.), Metal depletion potential (MDP, kg Cu eq.), Ionizing radiation (IRP, kBq Co-60 eq. to air), Freshwater eutrophication potential (FEP, kg P eq.), Marine eutrophication (MEP, kg N eq.), Terrestrial eutrophication (TEP, kg 1,4 DCB eq.), Photochemical oxidant formation potential, human health (POFPH, kg NO_x eq.), Photochemical oxidant formation potential, ecosystem (POFPE, kg NO_x eq.), Freshwater ecotoxicity potential (FETP, kg 1,4 DCB eq.), Human toxicity potential, cancer (HTPc, kg 1,4 DCB eq.), Marine ecotoxicity potential (METP, kg 1,4 DCB eq.), Human toxicity potential, non-cancer (HTP nc, kg 1,4 DCB eq.).

Further endpoint impacts were evaluated it in 22 impact categories aggregating into total 3 damages namely damage to ecosystem, human health and resources. The endpoint impact categories which are accountable for damage to ecosystem are described as follows (all have unit of species/year): Climate Change - Freshwater Ecosystem (CC-FE), Climate Change - Terrestrial Ecosystem (CC-TE), Freshwater Eutrophication (FC-FW), Terrestrial Eutrophication (FC-TE), Freshwater Ecotoxicity (FET), Freshwater Eutrophication Uncertainty (FEU), Land Occupation (LO), Metal Depletion - Ecosystem (MET), Mineral Extraction Uncertainty (MEU), Terrestrial Acidification (TA), Photochemical Ozone Formation - Ecosystem (POF-E), and Terrestrial Ecotoxicity (TET).

Further, the endpoint impact categories which are aggregated as damage to human health are described as follows (all have unit of DALY i.e. Disability-Adjusted Life Year): Climate

Change - Human Health (CC-HH), Particulate Matter Formation (PMF), Freshwater Consumption - Human Health (FC-HH), Human Toxicity – cancer effects (HT c), Human Toxicity – non-carcinogenic effects (HT nc), Ionizing Radiation (IR), Photochemical Ozone Formation – Human Health Impact (POF-HHI), and Stratospheric Ozone Depletion (SOD).

The depletion in resources is divided into two categories namely depletion in metal and fossil in the unit of USD ($).

S4 Single parameter sensitivity and Montecarlo uncertainty analysis

To evaluate the impact of the individual parametric variations (through ±20% of the base value) of different considered parameters (such as, aluminium electrode consumption, total electricity consumption, transportation distance, and arsenic removals) on the values of environmental impacts; single parameter sensitivity analysis has been performed by assessing the parameters disparity through considering only single parameter variation at a time and keeping all others factors fixed at their pre-determined values.

In contrast to single parameter sensitivity analysis which considers variation of individual parameter only two or more factors might interact at a time. Therefore, assessing the simultaneous interaction and/or variation in the above-mentioned parameters (±20% range), Monte Carlo simulations were performed with 1000 iterations. Further, both normal distribution and uniform distribution were used to evaluate the robustness of uncertainty analysis.

S5 Techno-economic analysis

The specific terms used in the TEA such as net cash flows, net present value, internal rate of return, profitability index and payback period are defined as follows along with their mathematical expressions:

S5.1 Net cash flow (NCF)

Cash flow is the movement of cash into and out of the company over a certain period. It is calculated by taking difference of net cash inflow and net cash outflow, as shown in equation (S1).

$$NCF = \Sigma inflow - \Sigma outflow \tag{S1}$$

The inflow in the present study are sales from the water and spent materials whereas outflows are OPEX and taxes.

S5.2 Net present value (NPV)

NPV is the tool to analyse the profitability of the project or investment. It is the value of all future cash flows (positive or negative) over entire life of an investment discounted to the present. It can be calculated using equation (S2).

$$NPV = \Sigma_{t=0}^{T}\left(\frac{CF_t}{(1+i)^t}\right) - C_o \tag{S2}$$

Here CF_t is the cash flow for the period of t, C_o is the initial investment, T is the entire life of project and i is the discount rate.

S5.3 Internal rate of return (IRR)

IRR is the matric used in the financial analysis to estimate the profitability of the project or potential investment. IRR is the discount rate which makes the net present value of all the cash flows equal to zero. Equation S3 can be used for evaluating the IRR.

$$NPV = \Sigma_{t=1}^{T}\left(\frac{CF_t}{(1+IRR)^t}\right) - C_o = 0 \tag{S3}$$

Here, IRR is the internal rate of return

S5.4 Profitability index (PI)

PI is a financial metric used to evaluate the attractiveness of an investment or project. It measures the ratio of the present value of future cash flows generated by the project to the initial investment required. Equation (S4) can be used to evaluate the PI.

$$PI = \frac{NPV + C_o}{C_o} = 1 + \left(\frac{NPV}{C_o}\right) \tag{S4}$$

S5.5 Payback period (PB)

Payback Period is the length of time required for an investment to generate cash flows sufficient to recover the initial cost of the investment. It measures how quickly the invested capital can be recouped but does not consider the time value of money or cash flows occurring after the payback period**.**

For even (uniform) cash flows,

$$Payback\ period\ = \frac{Cost\ of\ investment}{Average\ annual\ cash\ flow}$$

For uneven cash flows, calculate the cumulative cash inflows year by year until the initial investment is recovered.

Table S3 Economic parameters and assumptions in TEA

Particulars	Values	Particulars	Values
General parameters		***Labour costs***	
Tax rate	12% (Web-1)	Operator	INR 500 /operator / 8-hour shift (Web-2)
Interest rate	10% (Arora et al., 2018a; Banerjee et al., 2022)		
Economic life	20 years (Gadkari et al., 2023)	***Utilities costs***	
Operating hours	2800 to 8400 hours /year	Electricity	INR 8.25 /kWh (Web-3)
Plant capacity	1000 L per hour		
Number of weeks	52 /year		
Length of start-up period	2 weeks		
Depreciation method	Straight line (Arora et al., 2018b; Gadkari et al., 2023)	***Raw material costs***	
Salvage value	25% of the initial capital cost	Aluminum	INR 330 /kg (Web-4)
		Sodium chloride	INR 5 /kg (Web-5)
Product escalation	5% /year	***Product costs***	
Raw material escalation	4% /year	Water	INR 250 /m^3
Operating and maintenance labour escalation	10% /year	Spent sludge	INR 150 /kg (Web-6)
Utilities escalation	10% /year		

S5.6 Assumptions involved in the TEA analysis

1. The operation of the EC treatment plant has been considered for an 8-hour shift, in accordance with government manpower regulations (Web https://www.24hourslaw.com/law/legal-working-hours-in-india/)
2. The effect of electrode passivation in terms of an increase in power requirement has been considered. Based on the literature, a 10% increase in power requirement has been considered because of the passivation of electrodes.
3. The maintenance shutdowns for 8-, 16-, and 24-hour operation plants are considered as 5, 10, and 15 days, respectively. Less maintenance time is required for the 8- and 16-hour plants, as minor maintenance activities can be performed without a complete shutdown.

Table S4 Breakdown of capital expenditures (Figures are in INR)

Component	Base scenario	With solar (8 hr operation)	With solar (16 h operation)	With solar (24 h operation)
Equipment cost	1066000	1066000	1066000	1066000
Installation	200000	200000	200000	200000
Building cost	150000	150000	150000	150000
Utilities set-up	20000	20000	20000	20000
Contingency	100000	100000	100000	100000
Other field expenses	100000	100000	100000	100000
Solar power system	0	450000	750000	1050000
Total	1636000	2086000	2386000	2686000

Table S5 Equipment cost with approximated salvage value (Figures are in INR)

Component	Cost	Salvage value
EC reactor	25000	1000
EC stand	37500	10000
EC wiring	25000	5000
Power supply unit	500000	150000
Recirculation pump	18750	2000
Dosing pump for NaCl	9750	1000
Settling tank	250000	159198
Sand filter	37500	5000
Filter press	125000	30000
Overall piping system	37500	2000
Total	1636000	365198

S6 **Results and discussion**

Table S6 Absolute values of environmental impacts from the different reactor capacity scenarios

Impact category	**Unit**	**R_1**	**R_2**	**R_3**	**R_4**	**R_5 (Real field plant)**
GWP	kg CO2 eq.	4.52	3.62	2.81	2.48	1.55
PMFP	kg PM2.5 eq.	2.21E-03	1.92E-03	1.68E-03	1.42E-03	7.83E-04
FDP	kg oil eq.	1.42	1.10	8.57	7.57	4.72E-01
FCP	m3	3.52E-02	2.97E-02	2.63E-02	2.35E-02	1.15E-02
FETP	kg 1,4 DB eq.	-3.08E-02	-3.09E-02	-3.09E-02	-3.09E-02	8.80E-05
FEP	kg P eq.	1.72E-05	8.60E-06	5.30E-06	5.13E-06	3.99E-06
HTc	kg 1,4-DB eq.	-1.63E-01	-1.65E-01	-1.66E-01	-1.67E-01	2.92E-03
HTnc	kg 1,4-DB eq.	-4.38E+01	-4.37E+01	-4.37E+01	-4.37E+01	-5.57E-02
IRP	kBq Co-60 eq. to air	1.16E-01	8.47E-02	7.05E-02	6.10E-02	3.53E-02
LUP	Annual crop eq.·y	3.28E-01	1.69E-01	1.04E-01	1.00E-01	7.86E-02
METP	kg 1,4-DB eq.	-4.21E-02	-4.23E-02	-4.24E-02	-4.25E-02	3.53E-04
MEP	kg N eq.	1.29E-04	6.91E-05	4.40E-05	4.21E-05	3.17E-05
MDP	kg Cu eq.	1.60E-02	1.25E-02	1.07E-02	9.14E-03	5.15E-03
EPOFP	kg NOx eq.	5.73E-03	4.78E-03	3.94E-03	3.41E-03	2.01E-03
HPOFP	kg NOx eq.	5.70E-03	4.76E-03	3.91E-03	3.39E-03	2.00E-03
ODP	kg CFC-11 eq.	1.81E-06	1.18E-06	7.99E-07	7.43E-07	5.36E-07
TAP	kg SO2 eq.	6.99E-03	6.00E-03	5.23E-03	4.45E-03	2.45E-03
TEP	kg 1,4-DB eq.	8.22E-01	6.46E-01	5.11E-01	4.48E-01	2.76E-01

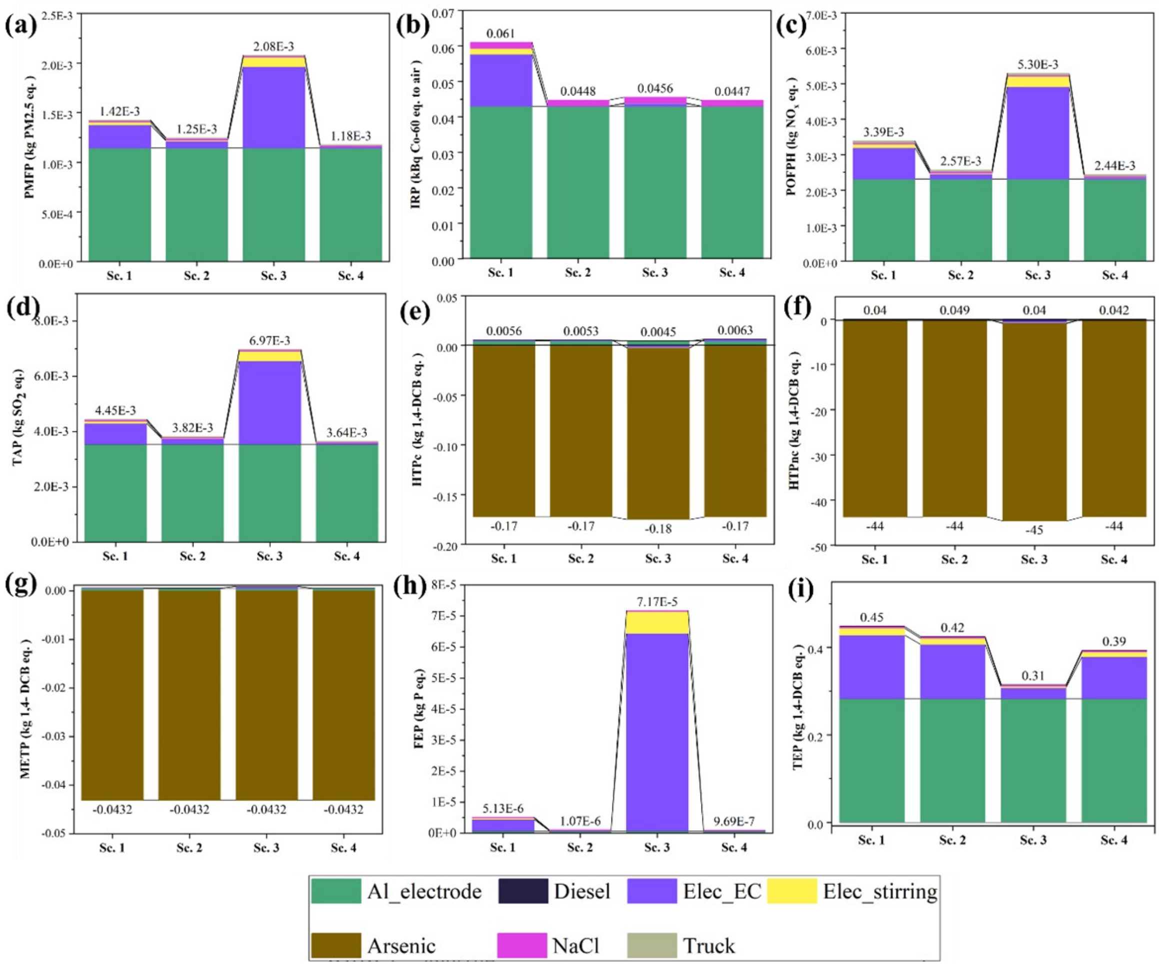

Figure S2 Environmental impacts from distinct electricity scenarios [Sc.1: Electricity from grid mix, Sc.2: Electricity from solar energy, Sc. 3: Electricity from biogas, Sc. 4: Electricity from wind energy] (a) PMFP, (b) IRP, (c) POFPH, (d) TAP, (e) HTP c, (f) HTP nc, (g) FDP, (h) POFPE and (i) MDP

Table S7: Absolute values of environmental impacts from the different electrical energy scenarios

Impact category	**Unit**	**Sc.-1**	**Sc. -2**	**Sc.-3**	**Sc.-4**
GWP	kg CO2 eq.	2.48	1.57	1.96	1.53
PMFP	kg PM2.5 eq.	1.42E-03	1.25E-03	2.08E-03	1.18E-03
FDP	kg oil eq.	7.57	4.82E-01	5.06E-01	4.70E-01
FCP	m3	2.35E-02	2.02E-02	3.00E-02	1.98E-02
FETP	kg 1,4 DB eq.	-3.09E-02	-3.10E-02	-3.07E-02	-3.10E-02
FEP	kg P eq.	5.13E-06	1.07E-06	7.17E-05	9.69E-07
HTc	kg 1,4-DB eq.	-1.67E-01	-1.67E-01	-1.71E-01	-1.66E-01
HTnc	kg 1,4-DB eq.	-4.37E+01	-4.37E+01	-4.46E+01	-4.37E+01
IRP	kBq Co-60 eq. to air	6.10E-02	4.48E-02	4.56E-02	4.47E-02
LUP	Annual crop eq.·y	1.00E-01	2.06E-02	1.22	1.94E-02
METP	kg 1,4-DB eq.	-4.25E-02	-4.26E-02	-4.22E-02	-4.26E-02
MEP	kg N eq.	4.21E-05	1.15E-05	4.64E-04	1.05E-05
MDP	kg Cu eq.	9.14E-03	7.67E-03	3.23E-02	7.81E-03
EPOFP	kg NOx eq.	3.41E-03	2.59E-03	5.34E-03	2.46E-03
HPOFP	kg NOx eq.	3.39E-03	2.57E-03	5.30E-03	2.44E-03
ODP	kg CFC-11 eq.	7.43E-07	2.75E-07	3.96E-06	2.65E-07
TAP	kg SO2 eq.	4.45E-03	3.82E-03	6.97E-03	3.64E-03
TEP	kg 1,4-DB eq.	4.48E-01	4.25E-01	3.15E-01	3.93E-01

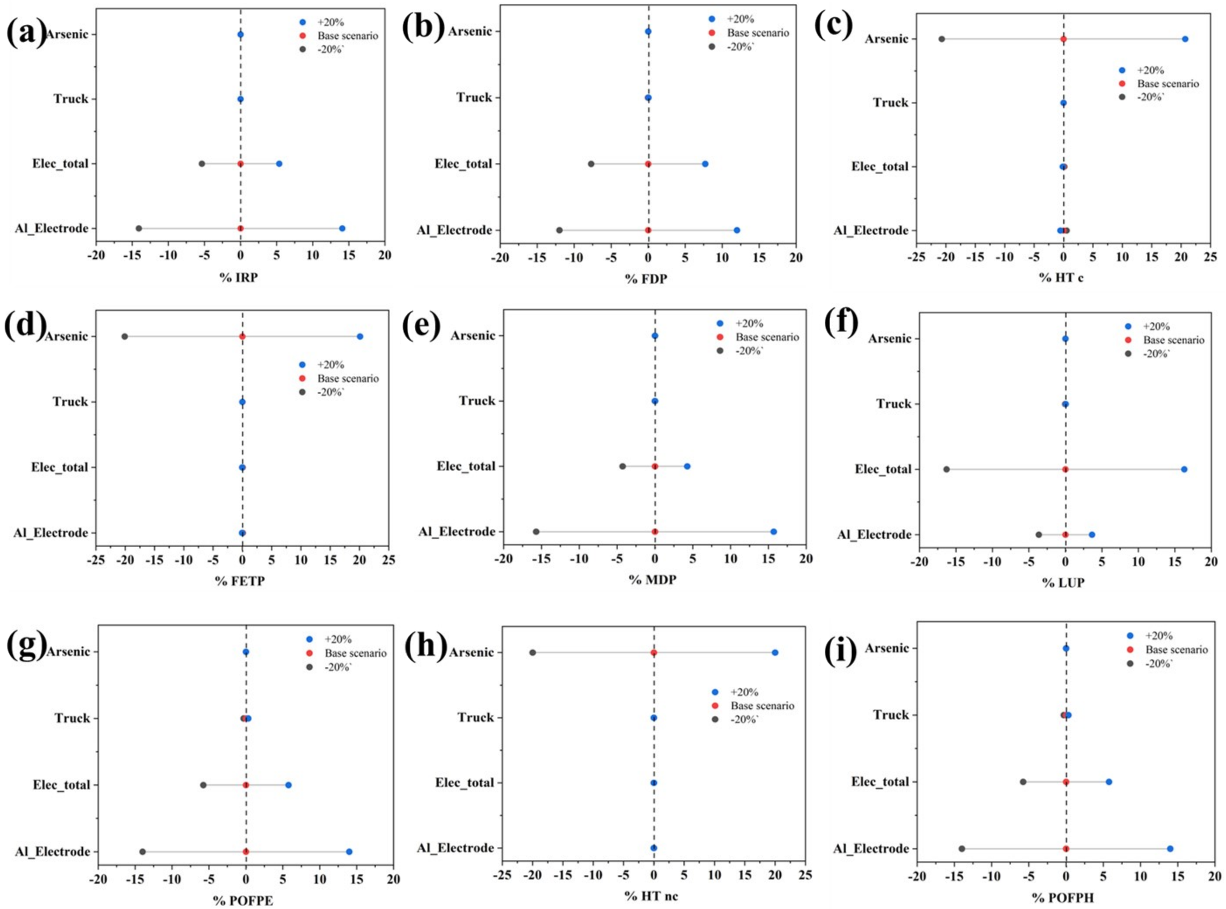

Figure S3 Impact of parametric sensitivity on the overall environmental impacts (a) IRP, (b) FDP, (c) HTc, (d) FETP, (e) MDP, (f) LUP, (g) POFPE, (h) HT nc and (i) POFPH

Table S8 Monte Carlo uncertainty analysis results considering the normal distribution for the 550 L (R_4) reactor process

Impact category	Unit	Basis scenario	Mean value	Standard deviation	10%	25%	Median	75%	90%
GWP	kg CO2 eq.	2.76	2.78	13.60%	2.31	2.53	2.78	3.02	3.26
PMFP	kg PM2.5 eq.	0.00142	0.00144	16.10%	0.00115	0.00129	0.00143	0.00159	0.00173
FDP	kg oil eq.	0.757	0.761	13.80%	0.63	0.692	0.762	0.83	0.897
FCP	m3	-15.5	-15.7	-17.40%	-19.1	-17.5	-15.6	-13.9	-12.2
FETP	kg 1,4 DB eq.	-0.0309	-0.0309	-20%	-0.0389	-0.035	-0.0311	-0.0266	-0.0227
FEP	kg P eq.	5.13E-06	5.12E-06	16.60%	4.07E-06	4.53E-06	5.12E-06	5.68E-06	6.18E-06
HT c	kg 1,4-DB eq.	-0.167	-0.167	-20.60%	-0.21	-0.189	-0.168	-0.143	-0.121
HT nc	kg 1,4-DB eq.	-43.7	-43.7	-19.90%	-55	-49.5	-43.9	-37.6	-32.1
IRP	kBq Co-60 eq. to air	0.061	0.0615	14.60%	0.0501	0.0555	0.0613	0.0674	0.0731
LUP	Annual crop eq.·y	0.1	0.1	16.60%	0.0793	0.089	0.1	0.111	0.121
METP	kg 1,4-DB eq.	-0.0425	-0.0425	-20.20%	-0.0536	-0.0482	-0.0427	-0.0365	-0.031
MEP	kg N eq.	4.21E-05	4.21E-05	15.50%	3.39E-05	3.77E-05	4.21E-05	4.64E-05	5.04E-05
MDP	kg Cu eq.	0.00914	0.00923	15.80%	0.0074	0.0083	0.00917	0.0102	0.0111
EPOFP	kg NOx eq.	0.00341	0.00344	14.60%	0.00279	0.0031	0.00342	0.00377	0.00408
HPOFP	kg NOx eq.	0.00339	0.00341	14.60%	0.00278	0.00308	0.0034	0.00374	0.00405
ODP	kg CFC-11 eq.	7.43E-07	7.44E-07	14.40%	6.09E-07	6.76E-07	7.43E-07	8.17E-07	8.79E-07
TAP	kg SO2 eq.	0.00445	0.00449	16%	0.0036	0.00402	0.00446	0.00496	0.0054
TEP	kg 1,4-DB eq.	0.448	0.451	14.10%	0.371	0.41	0.451	0.493	0.533

Table S9 Monte Carlo uncertainty analysis results considering the uniform distribution for the 550 L (R_4) reactor process

Impact category	Unit	Basis scenario	Mean value	Standard deviation	10%	25%	Median	75%	90%
GWP	kg CO2 eq.	2.76	2.76	7.99%	2.47	2.6	2.76	2.93	3.05
PMFP	kg PM2.5 eq.	0.00142	0.00142	9.40%	0.00124	0.00132	0.00141	0.00153	0.0016
FDP	kg oil eq.	0.757	0.756	8.09%	0.674	0.711	0.754	0.802	0.837
FCP	m3	-15.5	-15.4	-10.1%	-17.7	-16.7	-15.4	-14.2	-13.3
FETP	kg 1,4 DB eq.	-0.0309	-0.031	-11.4%	-0.0359	-0.0338	-0.031	-0.0279	-0.0261
FEP	kg P eq.	5.13E-06	5.15E-06	9.40%	4.48E-06	4.75E-06	5.15E-06	5.57E-06	5.80E-06
HT c	kg 1,4-DB eq.	-0.167	-0.167	-11.8%	-0.195	-0.183	-0.167	-0.15	-0.14
HT nc	kg 1,4-DB eq.	-43.7	-43.7	-11.4%	-50.7	-47.8	-43.8	-39.4	-36.9
IRP	kBq Co-60 eq. to air	0.061	0.0609	8.57%	0.0539	0.0568	0.0605	0.0652	0.0679
LUP	Annual crop eq.·y	0.1	0.1	9.46%	0.0875	0.0925	0.101	0.108	0.113
METP	kg 1,4-DB eq.	-0.0425	-0.0425	-11.6%	-0.0495	-0.0465	-0.0427	-0.0383	-0.0357
MEP	kg N eq.	4.21E-05	4.22E-05	8.84%	3.71E-05	3.91E-05	4.23E-05	4.54E-05	4.72E-05
MDP	kg Cu eq.	0.00914	0.00911	9.26%	0.00799	0.00847	0.00906	0.00982	0.0103
EPOFP	kg NOx eq.	0.00341	0.0034	8.59%	0.00301	0.00318	0.00339	0.00364	0.00379
HPOFP	kg NOx eq.	0.00339	0.00338	8.58%	0.00299	0.00316	0.00337	0.00361	0.00377
ODP	kg CFC-11 eq.	7.43E-07	7.44E-07	8.30%	6.61E-07	6.95E-07	7.44E-07	7.92E-07	8.27E-07
TAP	kg SO2 eq.	0.00445	0.00443	9.35%	0.00388	0.00411	0.00441	0.00478	0.005
TEP	kg 1,4-DB eq.	0.448	0.447	8.26%	0.398	0.42	0.447	0.476	0.496

Table S10 Comparison between the results of normal and uniform distributions

Impact category	Unit	Standard deviation			Median		
		Normal	Uniform	Difference (%)	Normal	Uniform	Difference
GWP	kg CO2 eq.	13.60%	7.99%	5.61%	2.78E+00	2.76E+00	0.72
PMFP	kg PM2.5 eq.	16.10%	9.40%	6.70%	1.43E-03	1.41E-03	1.40
FDP	kg oil eq.	13.80%	8.09%	5.71%	7.62E-01	7.54E-01	1.05
FCP	m3	-17.40%	-10.10%	-7.30%	-1.56E+01	-1.54E+01	1.28
FETP	kg 1,4 DB eq.	-20%	-11.40%	-8.60%	-3.11E-02	-3.10E-02	0.32
FEP	kg P eq.	16.60%	9.40%	7.20%	5.12E-06	5.15E-06	-0.59
HT c	kg 1,4-DB eq.	-20.60%	-11.80%	-8.80%	-1.68E-01	-1.67E-01	0.60
HT nc	kg 1,4-DB eq.	-19.90%	-11.40%	-8.50%	-4.39E+01	-4.38E+01	0.23
IRP	kBq Co-60 eq. to air	14.60%	8.57%	6.03%	6.13E-02	6.05E-02	1.31
LUP	Annual crop eq.·y	16.60%	9.46%	7.14%	1.00E-01	1.01E-01	-1.00
METP	kg 1,4-DB eq.	-20.20%	-11.60%	-8.60%	-4.27E-02	-4.27E-02	0.00
MEP	kg N eq.	15.50%	8.84%	6.66%	4.21E-05	4.23E-05	-0.48
MDP	kg Cu eq.	15.80%	9.26%	6.54%	9.17E-03	9.06E-03	1.20
EPOFP	kg NOx eq.	14.60%	8.59%	6.01%	3.42E-03	3.39E-03	0.88
HPOFP	kg NOx eq.	14.60%	8.58%	6.02%	3.40E-03	3.37E-03	0.88
ODP	kg CFC-11 eq.	14.40%	8.30%	6.10%	7.43E-07	7.44E-07	-0.13
TAP	kg SO2 eq.	16%	9.35%	6.65%	4.46E-03	4.41E-03	1.12
TEP	kg 1,4-DB eq.	14.10%	8.26%	5.84%	4.51E-01	4.47E-01	0.89

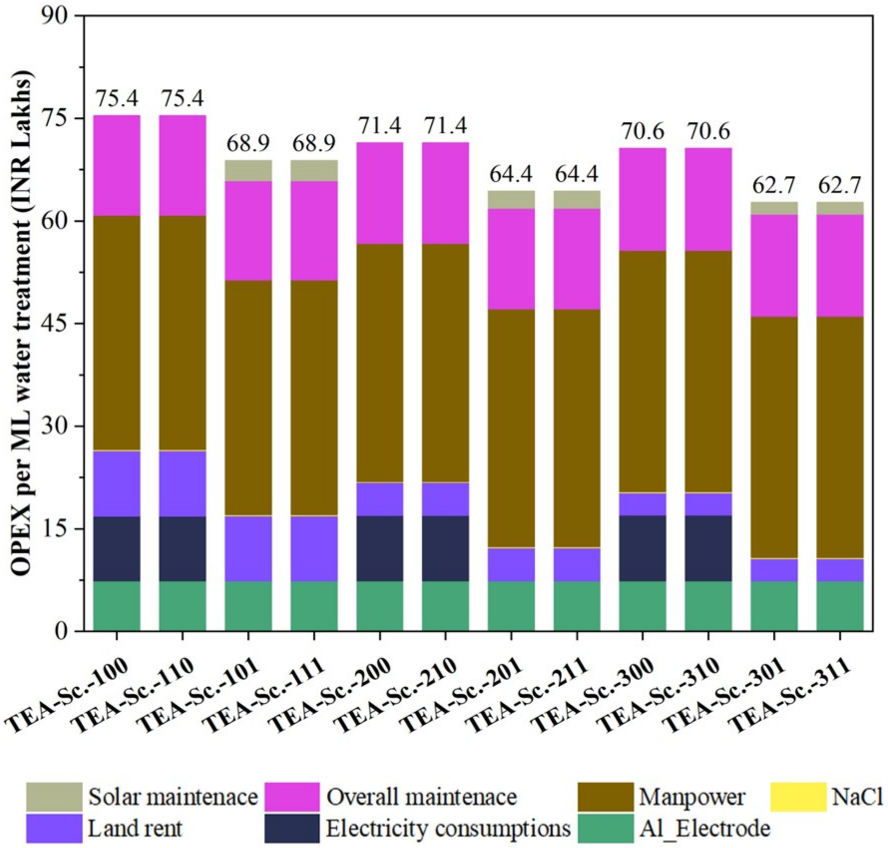

Figure S4 OPEX of the EC based water treatment system per Mega Liter (ML) of water treatment for different TEA scenarios

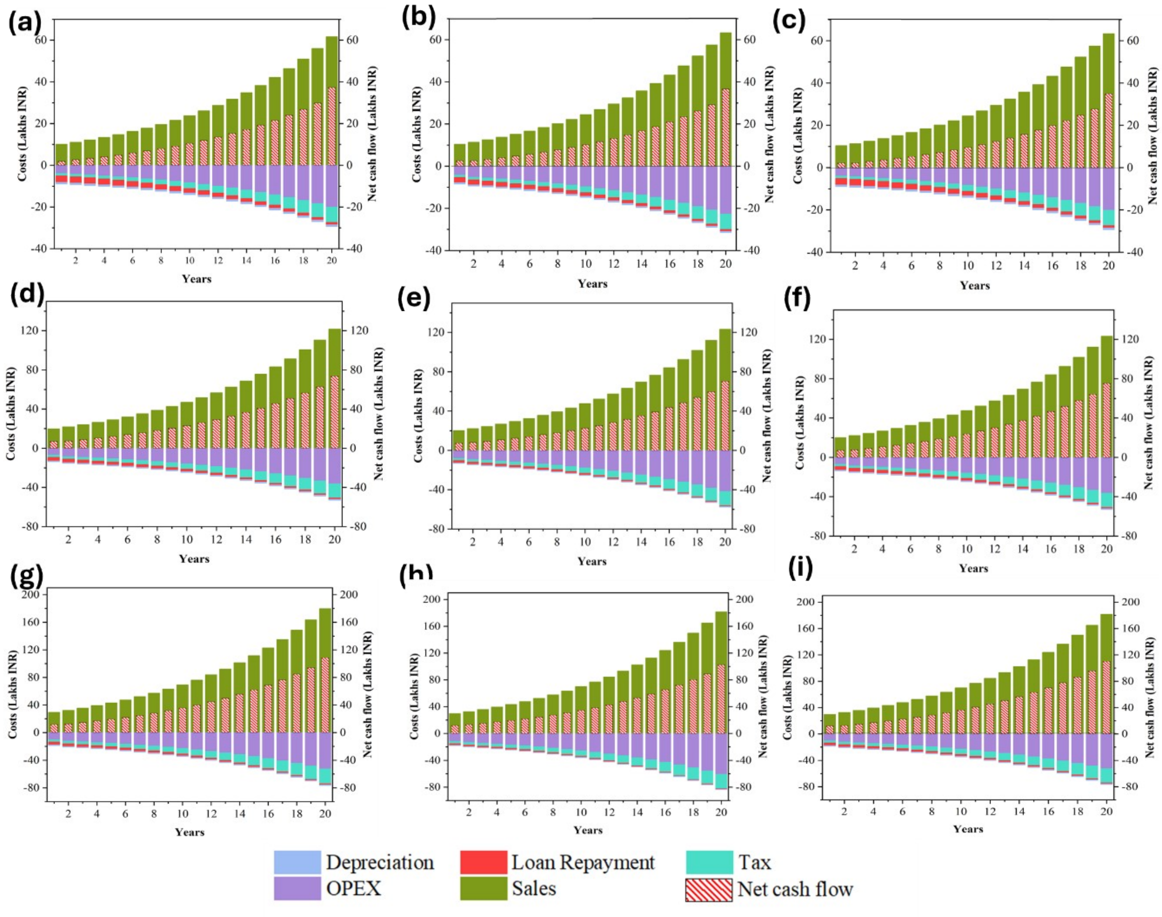

Figure S5 Cash flow and its breakdown into sales, operating cost, depreciation, tax and loan repayment (a) TEA_Sc._101, (b) TEA_Sc._110, (c) TEA_Sc._111, (d) TEA_Sc._201, (e) TEA_Sc._210, (f) TEA_Sc._211, (g) TEA_Sc._301, (h) TEA_Sc._310 and (i) TEA_Sc._311

S6.1 Comparison with previous studies

Comparison of the present work with earlier reports on adsorption, electrocoagulation, and reverse osmosis for water treatment is summarized in Table S7. Limited literature is available on integrated LCA and TEA studies for the simultaneous removal of arsenic and fluoride.Garfí et al., 2016 and Gani et al., 2023 reported LCA of RO systems for drinking water production that did not specifically target arsenic or fluoride. These studies showed relatively low GWP values of 1.6 and 0.05 kg CO_2 eq. per m^3, respectively. The comparatively higher GWP in the present study can be attributed to the complexity of arsenic and fluoride removal, which requires more specialised processes compared to the treatment of general water quality parameters. However, the operating cost of RO (up to INR 200 per m^3) was significantly higher than that of the present electrocoagulation system (INR 144 per m^3), highlighting the techno-economic advantage of the developed approach.

Adsorption-based treatment methods were mostly reported for individual arsenic or fluoride removal, except for the study by Goyal & Mondal, 2022 , which considered both contaminants together. LCA values reported by Rathore & Mondal, 2018 for fluoride removal and for arsenic removal were much higher than those obtained in the present work. Notably, Bisaria et al., 2024 reported a treatment cost of INR 13,142 per m^3 for arsenic removal, which is significantly higher compared to the present study (INR 144 per m^3). Even though Anweshan et al. 2025 reported lower treatment cost for fluoride removal (INR 20.41 per m^3), this can be explained by the fact that fluoride is relatively easier to remove than arsenic. Overall, adsorption processes demonstrate either high GWP or excessively high costs, limiting their sustainability in real-world applications.

The present study provides a novel integrated framework combining LCA and TEA for the simultaneous removal of arsenic and fluoride through electrocoagulation. Compared with adsorption- and RO-based alternatives, the developed process demonstrates a lower global warming potential as well as reduced treatment cost, especially for simultaneous removal of arsenic and fluoride. These findings confirm the potential of electrocoagulation as a more sustainable and economically viable option for arsenic- and fluoride-contaminated groundwater treatment, filling an important gap in the existing literature.

Table S11 Comparison with other treatment methods and previous EC studies

Contaminant	Process	LCA Method	LCA results	TEA		References
				CAPEX	OPEX	
Drinking water treatment	Reverse osmosis	CML FU: 1 m^3	1.6 kg CO_2 eq. per m^3	Not reported	Not reported	(Garfí et al., 2016)
Fluoride	Laterite soil-based adsorbent	CML FU: 720 L	16.57 kg CO_2 eq. per m^3	Not reported	Not reported	(Rathore & Mondal, 2018)
Arsenic and fluoride	AHNP-based adsorption	CML 2001 FU: 720 L	48.9 kg CO_2 eq. per m^3	Not reported	INR 700 per m^3	(Goyal & Mondal, 2022c)
Arsenic and fluoride	Electrocoagulation	CML 2001 FU: 720 L	6.25 kg CO_2 eq. per m^3	Not reported	INR 100 per m^3	(Goyal & Mondal, 2022c)
General water quality parameters (Except As and F)	Tap water supply from drinking water treatment plant	CML FU: 1 m^3 water	0.03 kg CO_2 eq. per m^3	Not reported	INR 22.31 per m^3	(Gani et al., 2023)
General water	Domestic RO	CML	0.05 kg CO_2 eq.	Not	INR 200 per	(Gani et al., 2023)

quality parameters (Except As and F)		FU: 1 m^3 water	per m^3	reported	m^3	
Arsenic	Adsorption (Ni-Fe layered double hydroxide)	ReCiPe method FU: 1 kg of adsorbent	33.54 kg CO_2 eq. per m^3	Not reported	INR 13142 per m^3	(Bisaria et al., 2024)
Fluoride	Electrocoagulation	FU: 2500 L/h	NA	INR 18.80 Lakhs	INR 20.41 per m^3	(Anweshan et al., 2025)
Arsenic and Fluoride	Electrocoagulation	ReCiPe FU: 1000 m^3	2.37 kg CO_2 eq. per m^3	INR 16.36 Lakhs	INR 144 per m^3	This study

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Weblinks

Web-1 https://www.paisabazaar.com/tax/gst-on-water/ (assessed on 1 Feb 2025)

Web-2 https://www.sgcms.com/regulatory-updates/minimum-rate-of-wages-chhattisgarh-april-2025/ (assessed on 15 June 2025)

Web-3 https://www.upcl.org/wp-content/uploads/2024/04/Public-Notice-Tariff-and-Charges-01-04-2024.pdf (assessed on 15 December 2024)

Web-4 https://economictimes.indiatimes.com/commoditysummary/symbol-ALUMINIUM.cms (assessed on 25 March 2025)

Web-5 https://dir.indiamart.com/impcat/sodium-chloride.html (assessed on 15 December 2024)

Web-6 https://www.indiamart.com/proddetail/gamma-alumina-catalyst-carriers-21305263988.html?srsltid=AfmBOorQoKQOIhNaa6N1g5xerGob6LXIunWQc-kH2JJxcvfSL8Fky4KI (assessed on 26 September 2025)