



Hybrid Electrocoagulation–Adsorption Treatment of Ammunition Manufacturing Wastewater: Influence of Process Parameters on COD, Heavy Metals And Sulfate Removal

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MACHINING
SURFACE TREATMENT
CLEANING OPERATIONS

From a Complex Challenge to a Cleaner Tomorrow

Integrated Electrocoagulation–Adsorption for the Treatment of
Ammunition Manufacturing Wastewater

COMPLEX INDUSTRIAL WASTEWATER

Heavy metals

Pb Cu Zn

Fe Mn

Sulfates

SO_4^{2-}

S

Suspended
solids

Oils & lubricants

Organic
compounds
(COD)

TOXIC | PERSISTENT | BIOACCUMULATIVE

A SIGNIFICANT ENVIRONMENTAL CHALLENGE

1. ELECTROCOAGULATION

- In-situ coagulant generation
- Destabilization
- Heavy metal removal
- Partial oxidation of organics
- Less chemical use, less sludge

2. ADSORPTION (POLISHING)

- Granular activated carbon (GAC) & biochar
- High surface area
- Removal of residual contaminants
- Sustainable and cost-effective



Simultaneous removal
of heavy metals, sulfate
and organic matter



Comparison of
different electrode
materials and adsorbents



Towards efficient
and sustainable
treatment strategies

CLEANER WATER
SAFER ENVIRONMENT
A SUSTAINABLE FUTURE

INDUSTRY | INNOVATION | ENVIRONMENTAL RESPONSIBILITY

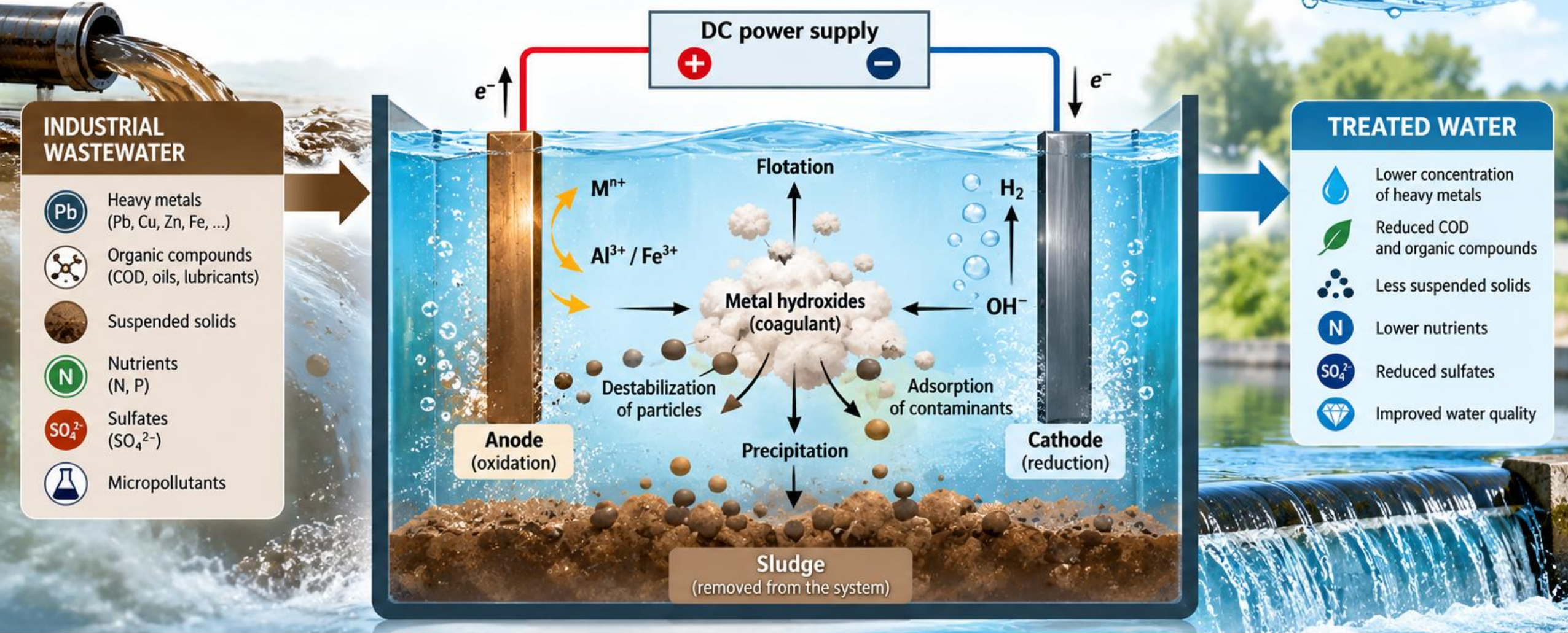
Cleaner Water
Safer Tomorrows

ELECTROCOAGULATION (EC)

CLEANER WATER THROUGH ELECTROCHEMISTRY

In-situ generated coagulants • Multi-contaminant removal • Less chemicals • Less sludge

From wastewater to a cleaner future



EFFECTIVE
removal of multiple contaminants



LOWER CHEMICAL CONSUMPTION
and less sludge



VERSATILE AND SCALABLE
for industrial wastewaters



A MORE SUSTAINABLE
CLEANER ENVIRONMENT

Hybrid Electrocoagulation-Adsorption (EC-Ads)

Synergistic treatment for complex industrial wastewaters

*Cleaner water
Greater future*

RAW WASTEWATER

- Pb** Heavy metals (Pb, Cu, Zn, Fe, ...)
-  Organic compounds (COD, oils, lubricants)
-  Suspended solids
- N** Nutrients (N, P)
- SO₄²⁻** Sulfates (SO₄²⁻)
-  Micropollutants

1. ADSORPTION

Binding of contaminants to the surface of adsorbents

2. ELECTROCOAGULATION

In-situ generation of coagulants and destabilization of particles



TREATED WATER



-  Lower concentration of heavy metals
-  Reduced COD and organic compounds
-  Less suspended solids
- N** Lower nutrients
- SO₄²⁻** Reduced sulfates
-  Improved water quality

ADDITIONAL BENEFITS OF ADDING ADSORPTION

- ✓ Removal of residual dissolved contaminants after EC
- ✓ Improved removal of refractory organic compounds
- ✓ Enhanced heavy metal and sulfate removal
- ✓ Polishing of treated water to meet stricter discharge limits
- ✓ Lower overall chemical consumption
- ✓ Complementary and synergistic removal mechanisms
- ✓ More stable and robust treatment performance

Spent adsorbent

(with adsorbed contaminants)

Sludge

(aggregated particles and adsorbed contaminants)



EFFECTIVE
MULTI-CONTAMINANT REMOVAL



LOWER CHEMICAL USE
AND LESS SLUDGE



SUSTAINABLE AND
COST-EFFECTIVE SOLUTION



CLOSING THE LOOP
FOR A CLEANER ENVIRONMENT

AMMUNITION MANUFACTURING WASTEWATER

A COMPLEX AND CHALLENGING WASTEWATER MATRIX

FROM INDUSTRIAL
CHALLENGES
TO CLEANER
TOMORROWS 



Machining

Metalworking fluids,
lubricants, oils



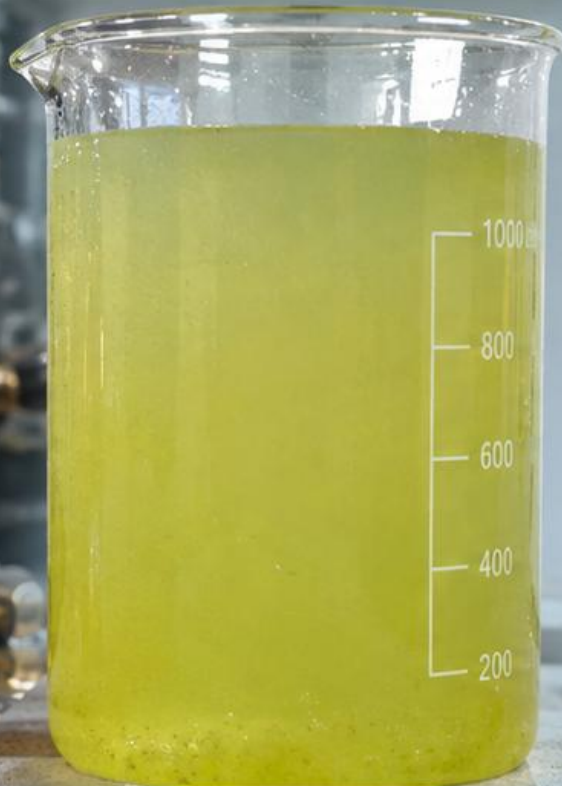
Surface treatment

Metals, sulfates,
cleaning agents



Cleaning operations

Detergents, organic
compounds



Actual wastewater sample
(from this study)

*Different production processes
generate a complex wastewater
with highly variable composition.*

Initial physicochemical characteristics of the investigated ammunition manufacturing wastewater

Parameter	Measurement unit	Value
pH	–	7.03
Electrical conductivity	μS/cm	1478
TDS	ppm	795
Turbidity	FNU	46
COD	mg O ₂ /L	38
Sulfates	mg/L	575
Al	mg/L	0.38
Cu	mg/L	0.16
Fe	mg/L	0.01
Mg	mg/L	22.75
Mn	mg/L	0.11
Pb	mg/L	0.97
Si	mg/L	6.82
Zn	mg/L	0.67

KEY CONSTITUENTS AND CONCERNS



Heavy metals (Pb, Cu, Zn, Fe, Mn, ...)

Toxic, persistent,
bioaccumulative



Sulfates

High concentrations,
can cause salinity, odour
(H₂S) and corrosion



Organic compounds

(COD, oils, lubricants,
cleaning agents)
Often refractory



Suspended solids

Contribute to turbidity
and treatment complexity



Nutrients (N, P)

May promote biological
growth

WHY IT IS CHALLENGING?



Complex mixture
of inorganic and organic
contaminants



Highly variable
composition and
concentrations



Presence of toxic
and persistent pollutants



Requires advanced
treatment technologies
for efficient removal



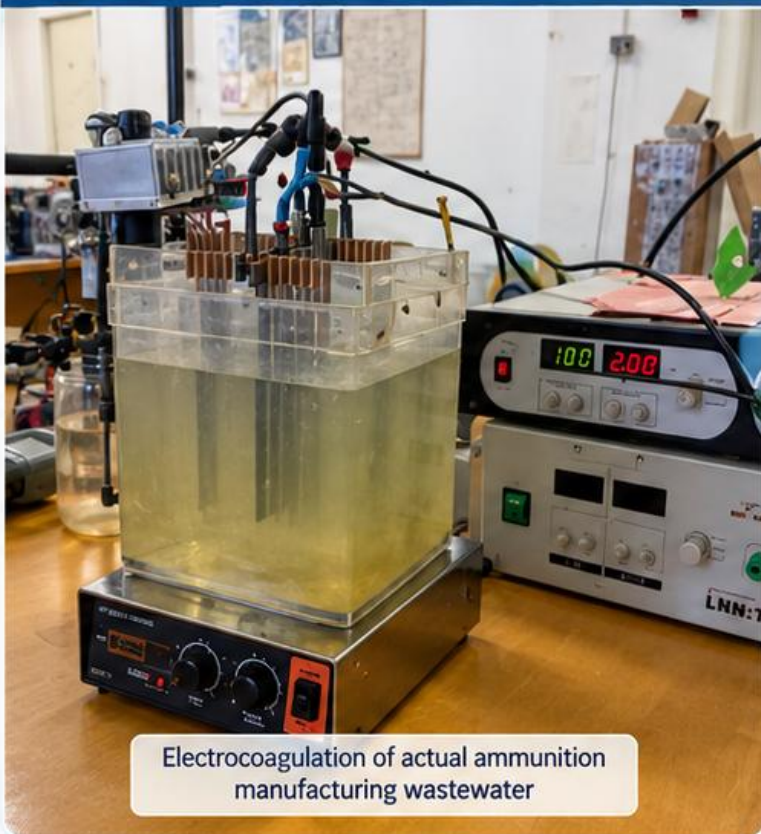
UNDERSTANDING
THE WASTEWATER
IS THE FIRST STEP
TOWARDS A CLEANER
ENVIRONMENT

EXPERIMENTAL SET-UP

Hybrid electrocoagulation–adsorption system for the treatment of ammunition manufacturing wastewater

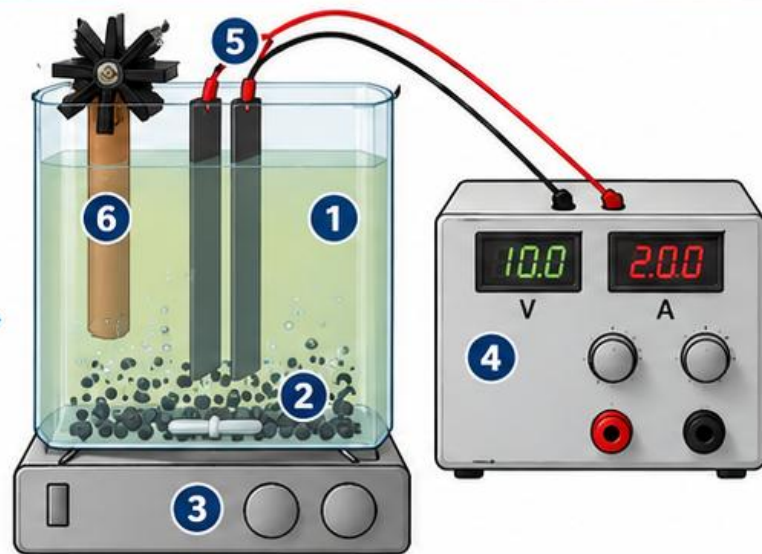
*From complex wastewater
to cleaner water*

LABORATORY SET-UP (REAL PHOTO)



Electrocoagulation of actual ammunition manufacturing wastewater

SCHEMATIC DIAGRAM



- 1 EC reactor (transparent acrylic)
- 2 Adsorbent (GAC / Biochar)
- 3 Magnetic stirrer (200 rpm)
- 4 DC power supply (adjustable voltage/current)
- 5 Interchangeable plate electrodes (Fe, Al, C, Pb)
- 6 Cooling element (heat pipe, heat sink and fan)

KEY EQUIPMENT AND COMPONENTS



Interchangeable electrodes
(Fe, Al, C, Pb)



Cooling element
(heat pipe, heat sink and fan)



DC power supply
(0–30 V, 0–10 A)



Magnetic stirrer
(200 rpm)



Acrylic reactor
(2.5 L working volume)



Adsorbents:
GAC, Biochar 1 (BC1),
Biochar 2 (BC2)

INVESTIGATED ELECTRODE CONFIGURATIONS



EXPERIMENTAL PROGRAM

1 ADSORBENT SCREENING

- GAC, Biochar 1 (BC1), Biochar 2 (BC2)
- 200 mL wastewater, 10 g/L (2 g)
- Contact time: 120 min
- Mixing: 200 rpm
- Samples every 30 min



2 ELECTRODE CONFIGURATION SELECTION

- Fe/Fe, Fe/C, Al/Al, Al/C (and Pb/C)
- 2.5 L wastewater
- Treatment time: 30 min
- Mixing: 200 rpm
- Electrode spacing: 1 cm
- Settling: 15 min
- Samples every 10 min



3 EFFECT OF CURRENT INTENSITY

- Selected electrode configuration
- Applied current: 3, 6, 9 A
- Evaluation: pollutant removal, energy consumption, sludge production, pH variation, electrode dissolution



4 HYBRID EC-ADSORPTION EXPERIMENTS

- Integrated process evaluation
- Optimisation of operating conditions
- Simultaneous removal of heavy metals, sulfate and organic matter



Towards an efficient
and sustainable treatment solution

HYBRID EC-ADSORPTION PROCESS CONFIGURATIONS

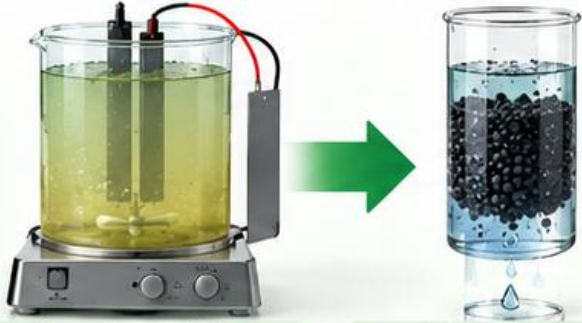
Different treatment sequences – towards optimal performance

Integrated solutions
for cleaner water

1

EC → ADS

Electrocoagulation followed by adsorption



Electrocoagulation (EC)

Adsorption (ADS)

Removal of suspended solids, heavy metals and part of organic compounds

Polishing of treated water (removal of residual contaminants)

2

ADS → EC

Adsorption followed by electrocoagulation



Adsorption (ADS)

Electrocoagulation (EC)

Pre-removal of organics and part of heavy metals

Further removal of contaminants and destabilization of particles

3

EC + ADS

Simultaneous electrocoagulation and adsorption



EC + ADS (simultaneous)

Synergistic interactions within a single reactor – simultaneous removal of heavy metals, sulfate and organic compounds



VERIFICATION EXPERIMENT

Pb/C electrode configuration under optimal hybrid conditions



Pb (anode)



C (cathode)



Evaluate the influence of lead electrodes on sulfate removal and overall treatment efficiency

ANALYTICAL METHODS

Comprehensive monitoring of water quality

Physicochemical parameters



- ✓ pH
- ✓ Electrical conductivity
- ✓ TDS
- ✓ Turbidity
- ✓ Temperature

HI 9829 multimeter (Hanna Instruments)

Chemical oxygen demand (COD)



- Photometric determination
- NANOCOLOR 500D (Macherey-Nagel)
- NANOCOLOR CSB 60 test kits
- Thermal digestion (NANOCOLOR VARIO)

Heavy metals



- Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES)
- Agilent 5900 SVDV ICP-OES
- Simultaneous axial and radial observation
- Quantification using ICP Expert software

Sulfates



- UV-Vis spectrophotometry
- Cary 60 UV-Vis spectrophotometer
- Barium chloride turbidimetric method
- Commercial reagent packets

Reliable analysis for a comprehensive evaluation of treatment efficiency



COMPARISON OF TREATMENT SEQUENCES



OPTIMISATION OF PROCESS PERFORMANCE



VERIFICATION WITH Pb/C ELECTRODES



MULTI-PARAMETER ANALYSIS FOR A HOLISTIC ASSESSMENT



From complex wastewater to valuable knowledge

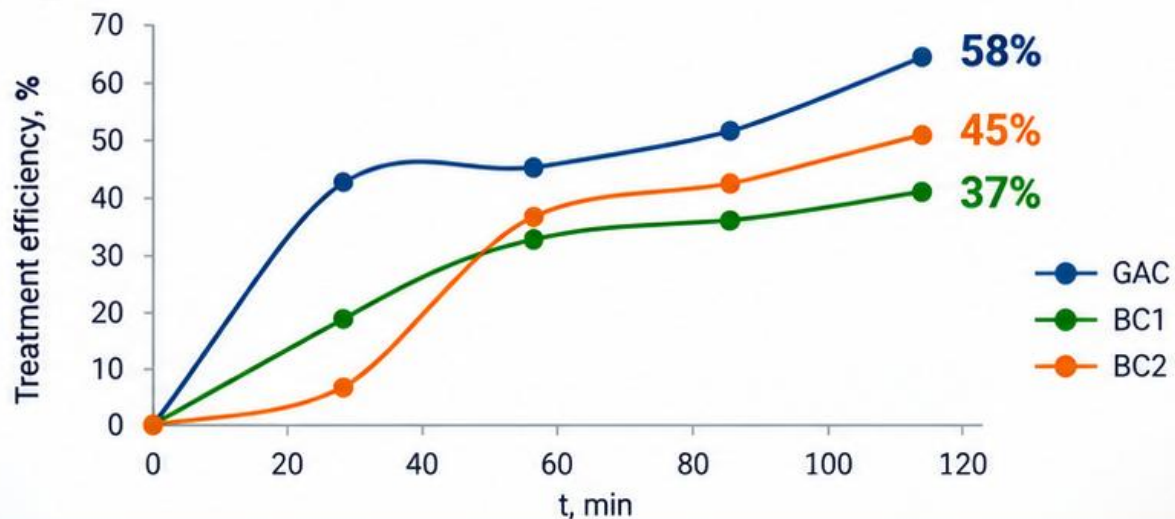
RESULTS – Selection of the Adsorbent

Comparative adsorption performance of GAC, BC1 and BC2



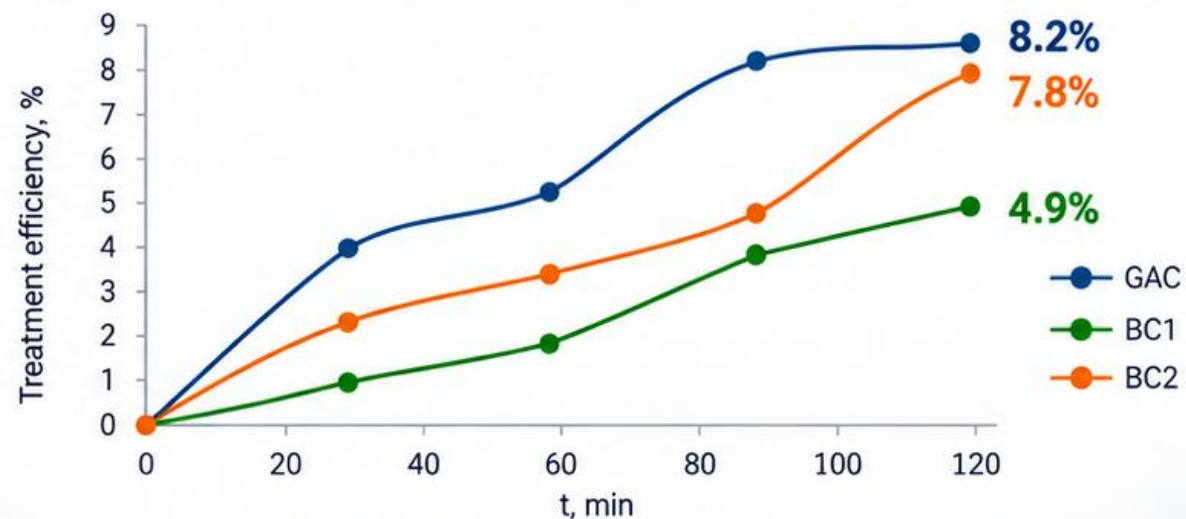
COD REMOVAL

Efficiency of COD removal by adsorption



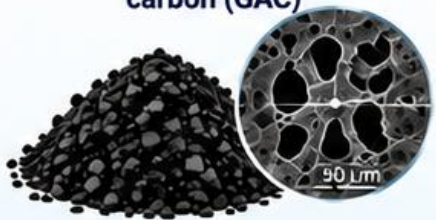
SULFATE REMOVAL

Efficiency of sulfates removal by adsorption

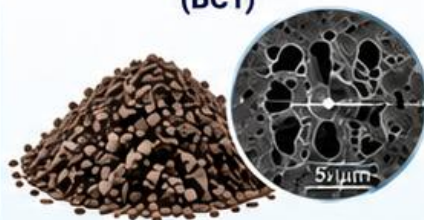


Investigated adsorbents

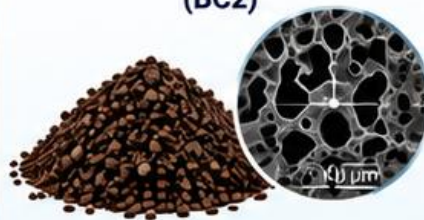
Granular activated carbon (GAC)



Biochar 1 (BC1)



Biochar 2 (BC2)



Experimental conditions

- 200 mL wastewater
- 10 g/L adsorbent
- 120 min
- 200 rpm
- Natural pH

Main outcome



GAC

selected as the adsorbent for subsequent hybrid electrocoagulation-adsorption experiments.



Higher pollutant removal



Effective under identical conditions



A step towards cleaner industrial wastewater

From complex water
to real solutions.

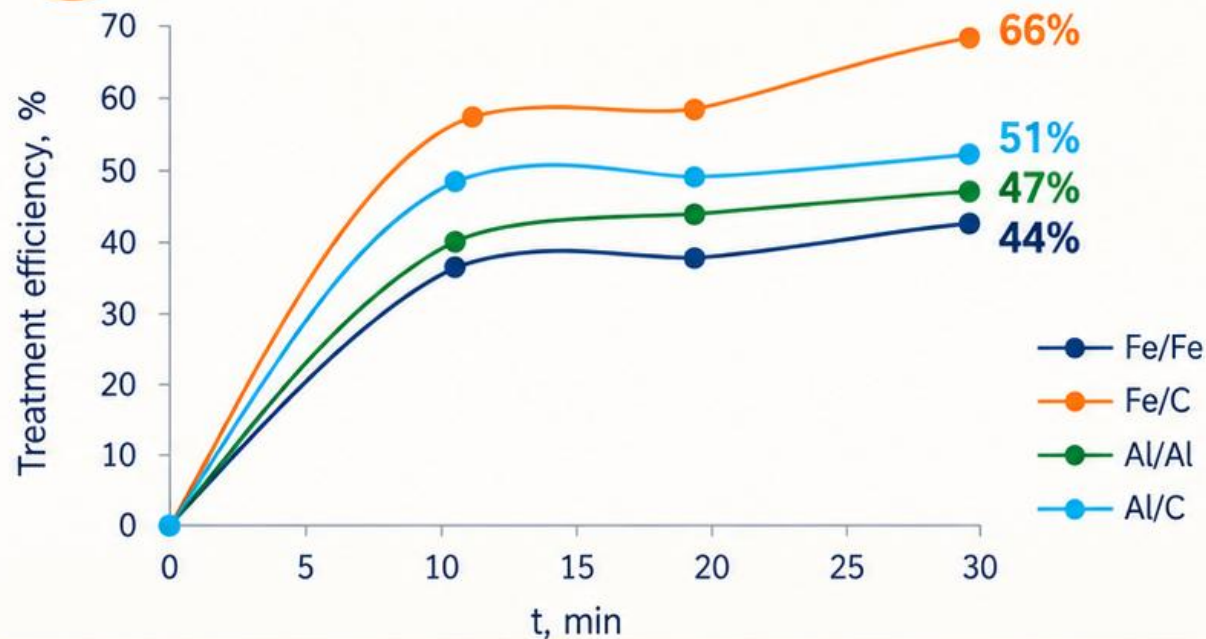
RESULTS – Selection of the Electrocoagulation Configuration

Effect of electrode material on COD and sulfate removal ($I = 3\text{ A}$)

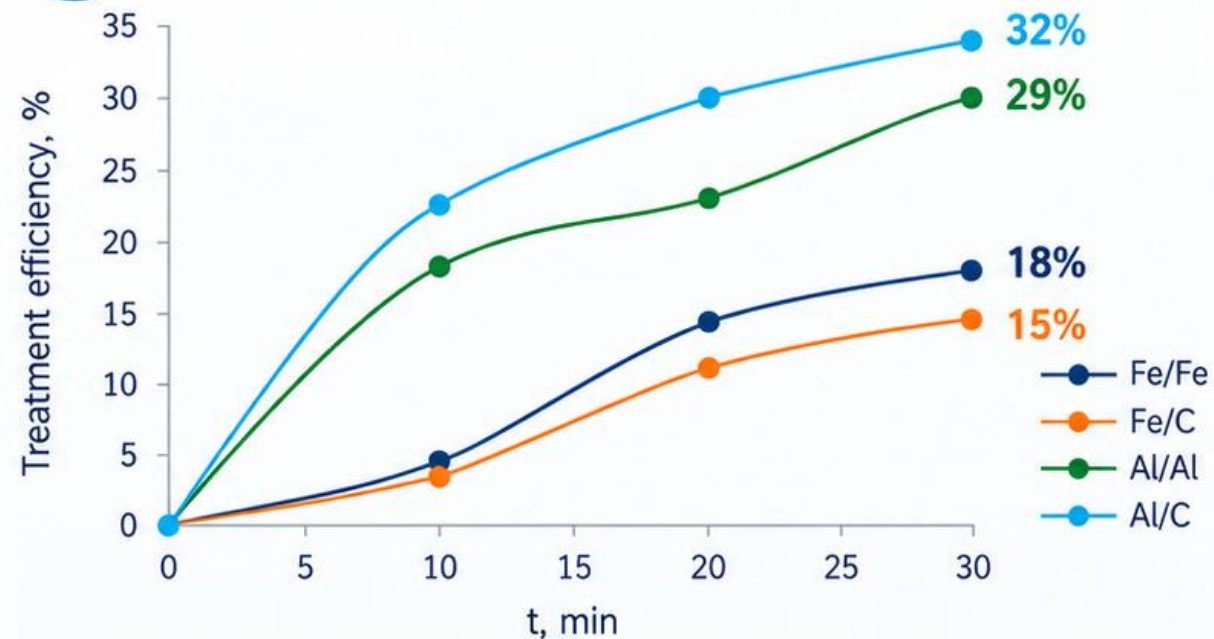
*Different electrodes.
Clearer water.*



COD REMOVAL ($I = 3\text{ A}$)



SULFATE REMOVAL ($I = 3\text{ A}$)



Electrode configurations

Fe/Fe



Fe/C



Al/Al



Al/C



Treated wastewater after 30 min ($I = 3\text{ A}$)

Fe/Fe



Fe/C



Al/Al



Al/C



Main outcome



Al/C

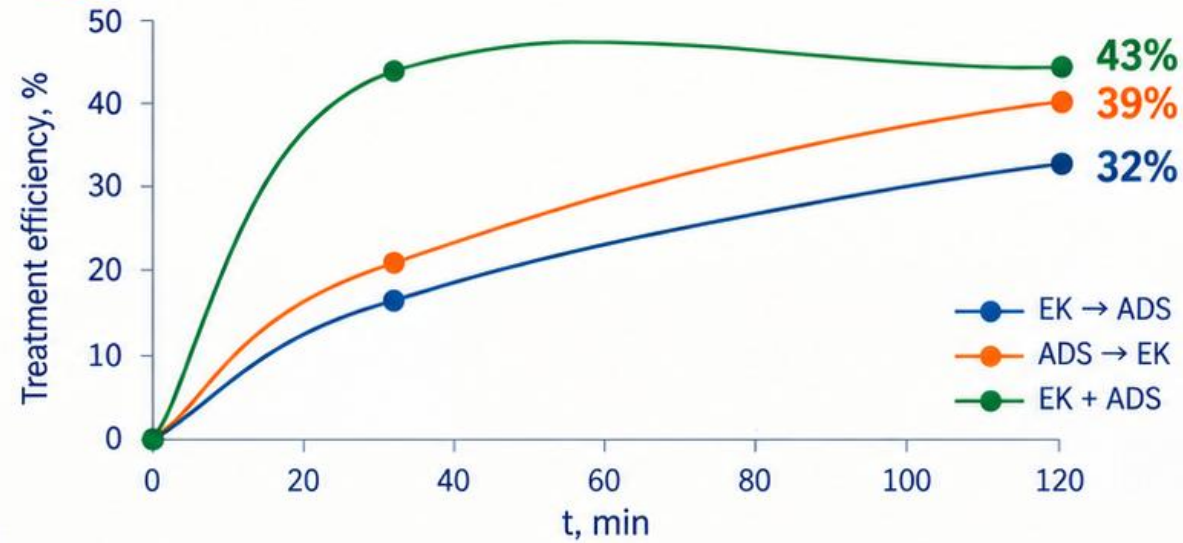
highest COD ($\approx 51\%$)
and sulfate removal ($\approx 32\%$)
after 30 min.

RESULTS – Performance of the Hybrid Electrocoagulation-Adsorption Process

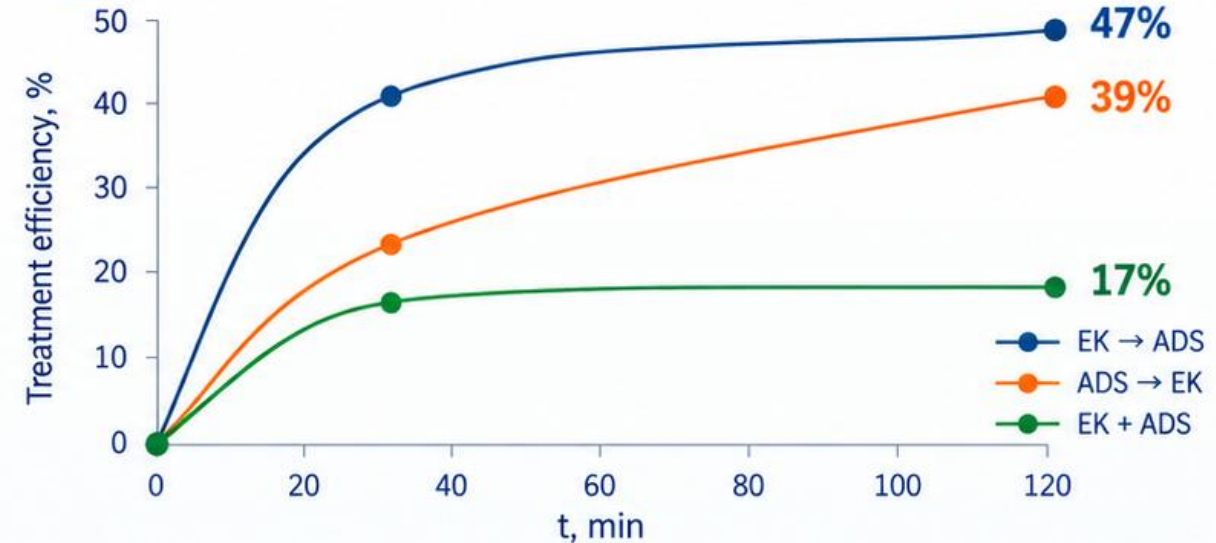
Effect of process configuration on COD and sulfate removal

Integrated solutions
for cleaner water.

COD REMOVAL



SULFATE REMOVAL



Hybrid process configurations (Al/C, 9 A, 30 min EC; GAC, 120 min ADS)



Key findings

- Highest COD removal:** EK + ADS (≈ 43%)
- Highest sulfate removal:** EK → ADS (≈ 47%)
- Process sequence affects treatment efficiency.
- Hybrid process outperforms individual processes.

Towards real applications

- Effective multi-barrier treatment for complex industrial wastewater.
- Further optimisation needed (adsorbent capacity, energy and electrodes).
- Basis for scale-up and practical application.



CLEANER INDUSTRY



HEALTHIER ENVIRONMENT



SUSTAINABLE TOMORROW

CONCLUSIONS

Hybrid electrocoagulation–adsorption for cleaner industrial wastewater

*Cleaner industry.
Healthier tomorrow.*

1

Effective approach

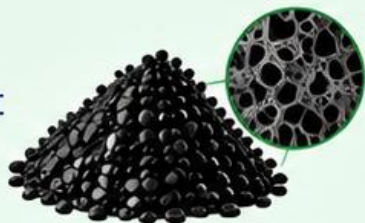
Hybrid EC–ADS effectively treats ammunition wastewater.



2

Best adsorbent

GAC showed the highest treatment performance.



3

Optimal EC conditions

Al/C, 9 A, 30 min provided the best performance and stability.



4

High heavy metal removal

Both processes achieved very high removal efficiencies for dissolved metals.



5

Improved COD and sulfate removal

Hybrid process enhances removal of COD and sulfates compared to individual processes.



6

Process sequence matters

Highest COD: **EC + ADS** (simultaneous).

Highest sulfate: **EC → ADS** (sequential).



7

Multi-barrier treatment

Combines EC and ADS for simultaneous removal of organic matter, sulfates and heavy metals.



8

Future outlook

Further optimisation under continuous flow (capacity, energy, electrode consumption) before pilot-scale application.



**CLEANER
WATER
SAFER
TOMORROW**

*Integrated solutions
for a sustainable future.*



SCIENCE



INNOVATION



CLEANER ENVIRONMENT

*Same water.
A brighter future.*



Thank you for your attention!

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