Factsheet

Acidic Deep Eutectic Solvents

for the Recovery of Critical Metals from Waste and Wastewater

waterproof-project.eu

A Rising Star: Acidic Deep Eutectic Solvents (ADES)

An emerging and promising method for the recovery of critical metals from waste and wastewater are Acidic Deep Eutectic Solvents (ADES). Within the EU-funded project WaterProof, these ADES are synthesised from the base chemical formic acid. This formic acid is a renewable feedstock as it is gained by electrochemical conversion of CO_2 emissions from waste and wastewater treatment plants.

ADES are a type of ionic solvents that consist of a hydrogen bond donor (formic acid in the case of WaterProof) and a hydrogen bond acceptor[1]. This way, ADES dissolve metals present in wastewater sludge and waste incineration ash by binding to these chemical elements via hydrogen bonds and formation of metal-ADES complexes that can be separated from the residual waste material.

Important features of ADES are their often low toxicity, biodegradability, customisable properties and high metal selectivity[2,3], which enable the precise recovery of valuable metals from complex waste streams under mild and energy-efficient conditions.

The development of ADES has high potential as a sustainable and pioneering method, and might offer the solution for low concentration recovery due to its high efficiency and selectivity for different metal types.

The Challenge of Critical Metals Recovery

Critical metals are chemical elements that are of high economic importance due to their scarcity, potential shortage or supply disruption, their use in important industrial applications, or their cultural significance (e.g. for jewellery or investment).

Concerning the EU economy, the extraction sites are often located in third countries, which results in a relationship of dependency. A solution is offered by recovering critical metals from secondary raw materials (such as wastewater sludge and waste incineration ash). This way, recovery of metals aligns with circular economy goals, and enables waste valorisation, offering both environmental and financial benefits.

Reintroducing recovered metals into manufacturing supply chains improves circularity and reduces the wastage of scarce raw materials through recycling and reuse. However, these valuable resources are often lost because of insufficient, energy- and cost-intensive recovery methods which in addition are often harmful/toxic for the environment (Info Box 1). Furthermore, the concentrations of metals in sewage sludge and waste incinerator ash are often low and therefore not so easy to recover.

Info Box 1

Why ADES? Weaknesses of Other Recovery Methods

Established Recovery Methods

Some other recovery methods are already in use. However, besides providing the advantage of metal recovery, they also come along with environmental and technical disadvantages:

→ **Physical and Mechanical Processes:** Include filtration, sedimentation, and centrifugation to separate metal particles from waste streams. Effective for coarse particles but inefficient for dissolved metals.

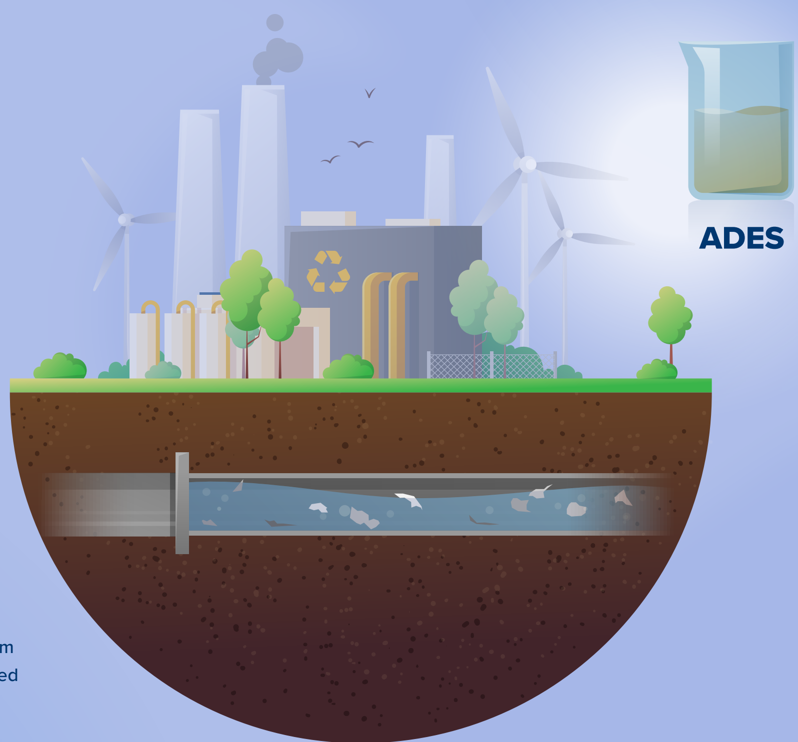
→ **Pyrometallurgical Processes:** High-temperature melting separates metals but consumes significant energy and emits pollutants. Suitable only for high-concentration feeds like electronic waste.

→ **Hydrometallurgical Processes:** Uses inorganic acids or toxic compounds such as cyanide leaching. Those processes are not selective and require downstream processes which increase opEX of the overall treatment plant.

Recovery Technologies Under Development

→ **Bio-Based Recovery:** Using bacteria (e.g., Chromo-bacterium violaceum) to selectively adsorb metals. Microorganisms or plant extracts selectively adsorb metals from wastewater. Eco-friendly but slower than chemical methods.

→ **Electrochemical Methods:** Membrane electrolysis and electrowinning enable selective metal extraction and recovery. Those technologies are excellent for treating liquid metal streams, but cannot deal with solid streams such as sludge and ashes.



Simplified illustration of the use of ADES for recovering metals from wastewater. ADES is not introduced directly into the sewage system; instead, recovery takes place in a reactor.

The Economic Value of Recovered Metals

The recovery of metals and elements, such as cobalt, copper, gold, silver, and palladium, from waste incineration ash, and copper, zinc and phosphorous from wastewater sludge is increasingly recognised for its economic and environmental benefits, and therefore as a relevant alternative to mining.

As critical metals are essential for various industries, their recovery is also financially profitable for the waste(water) treatment sector: Treatment plants can offset operational costs by selling the refined metals to smelters, jewellers, catalytic converter manufacturers and other industrial buyers. Furthermore, recovery provides an additional metal source, helping companies sustain operations during commodity price fluctuations and supply disruptions, thus supporting economic resilience.

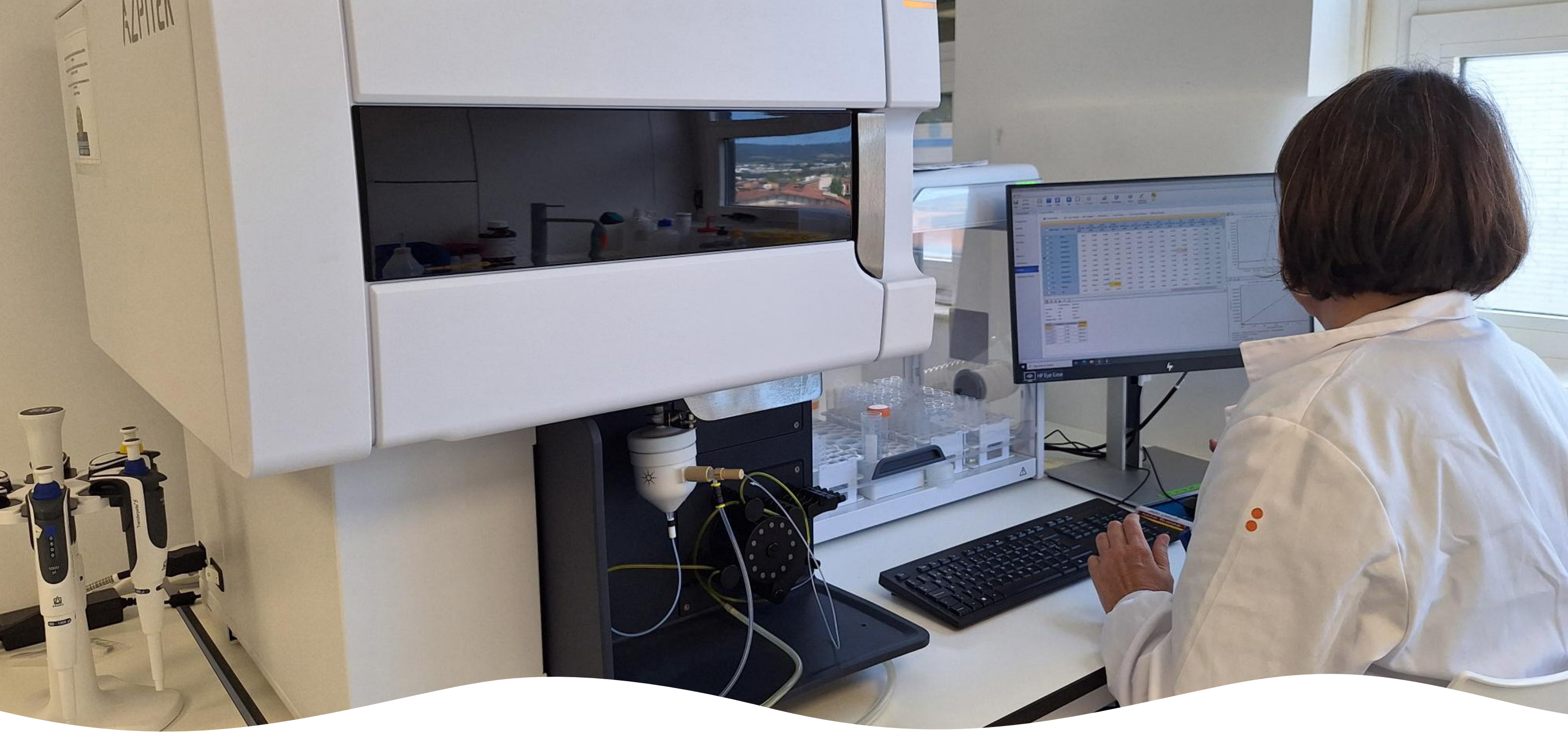
- **Cobalt:** Highly valued for use in batteries and electronics, cobalt is considered a critical raw material with volatile prices and strong demand growth[4].
- **Copper:** Widely used in electrical transmission and in construction, copper has a robust secondary market.[3]
- **Gold & Silver:** Gold and silver are among the most sought-after metals for recovery due to their high market value and extensive use in electronics and jewellery.[5]
- **Palladium:** Palladium belongs to platinum group metals (PGMs) and is essential for electronics and chemical industries. Its high value and scarcity make recovery especially attractive.

Recovered metals can achieve up to 4,000 – 12,000 USD per tonne[6], in case of recovered silver and gold, this price can even be as high as 1,000 USD per kg and 100,000 USD per kg respectively[7]. Furthermore, the global market for precious metals recovered from e-waste alone was valued at over 10 USD billion in 2023, with projections of continuous growth driven by high commodity prices and expanding e-waste volumes[8,9].

Info Box 2

Sources of Critical Metals in Waste and Wastewater

Critical metals, such as palladium, gold and silver, are found in many products, including waste electrical and electronic equipment (widely known as WEEE or e-waste), industrial plating, silver nanoparticles in antibacterial fabrics, food and food-additives, cosmetics (make-up) and pharmaceuticals. When these products are used, discarded, or washed down drains, the metals can be released into the environment. Even jewelry and alloys (e.g. in dental fillings and crowns) can slowly release metals. This can happen through rainwater runoff or routine washing. Another sink of precious metals are industrial discharges from mining, electronics manufacturing and metal plating. The discarded or eroded precious metals end up in wastewater sludge and waste incineration ash.



ADES: Challenges and Future Directions

While research on ADES is ongoing and has increased in recent years, widespread application of ADES is not yet feasible. This is because of several challenges:

→ **Technological Readiness and Scalability:**
ADES are subjects of research with more and more studies focussing on this topic in recent years (from 4,900 publications in 2019 to 18,400 in 2024[10]). However, they are not yet sufficiently developed to be produced in large quantities. Furthermore, the generation of ADES and associated costs remain hurdles for industrial adoption.

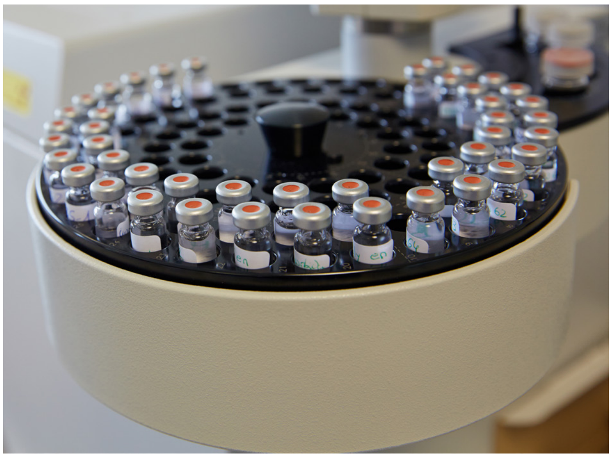
→ **Regulatory Gaps:**
Before widespread application, ADES-based metal recovery requires thorough environmental and safety assessments.

→ **Standardisation Gaps:**
Standard municipal waste and wastewater treatment plants are mostly not optimised for high-yield metal recovery. This is because specialised systems like decomplexation (i.e. breaking metal complexes in wastewater to release recoverable solids) and coagulation/flocculation (i.e. aggregating particles forming larger filterable flocs for easier separation) are often required to concentrate and extract metals efficiently.

Despite these challenges, ADES are highly suitable for process integration: Combining ADES with bio-recovery or electrochemical methods could optimise metal recovery efficiency.

Conclusion

It is advisable and economically relevant to recover critical metals and other elements such as phosphorous from secondary sources including wastewater sludge and incineration ashes, for which ADES offer an innovative technological solution. ADES and hybrid technologies offer sustainable, high-yield alternatives to traditional metal recovery aligning with circular economy goals (reuse and recycling). Research on ADES is ongoing, focussing on optimising selectivity and scalability for industrial deployment.



Relevant EU-Policies Related to Waste(water) and Metal Recovery

Waste Framework Directive (2008/98/EC): Promotes recycling and recovery of critical raw materials.

CLP Regulation (EC) No 1272/2008: Addresses hazardous substance classifications impacting metal recycling.

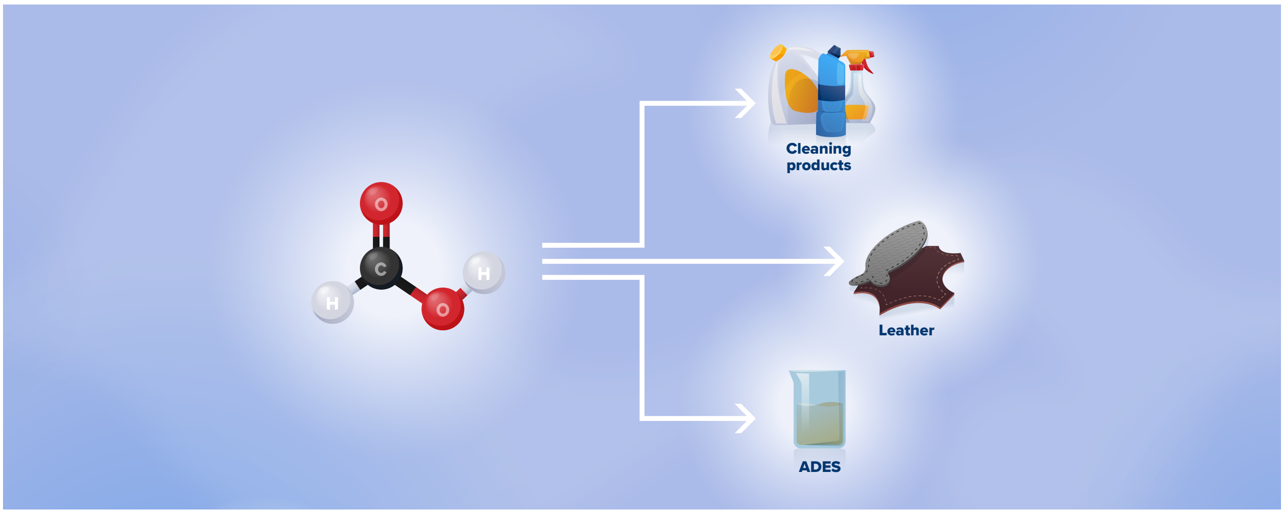
Circular Economy Action Plan: Encourages industrial symbiosis and efficient resource use in recycling.

The **WEEE Directive (2012/19/EU)** requires the separate collection and proper treatment of WEEE and sets targets for their collection, recovery and recycling. Because critical metals are of high-value and strategically important, WEEE recycling is directly linked to securing access to these metals within the EU.

About WaterProof

The WaterProof project aims to close the waste(water) carbon loop by developing a novel biorefinery concept that electrochemically converts CO_2 emissions from urban waste(water) treatment facilities into renewable formic acid, which is used for valuable green consumer products. The electrochemical process also generates peroxides as by-product that can be used to remove pharmaceuticals and pesticides from wastewater. The formic acid is further transformed into acidic deep eutectic solvents (ADES) for recovering critical metals from wastewater sludge and waste incineration ashes. ADES offer environmental advantages by replacing mineral acids and operating at lower energy requirements due to lower reaction temperatures[11].

Powered by renewable energy, the WaterProof approach contributes to a zero-emission clean water cycle, supporting the transition toward a climate-neutral Europe and a circular economy by integrating CO_2 utilisation, fossil feedstock replacement, precious metal recovery and industrial electrification.



References

1 Qin, H., Hu, X., Wang, J., Cheng, H., Chen, L., & Qi, Z. (2020). Overview of acidic deep eutectic solvents on synthesis, properties and applications. Green Energy & Environment, 5(1), 8-21.

2 Yuan, Z., Liu, H., Yong, W. F., She, Q., & Esteban, J. (2022). Status and advances of deep eutectic solvents for metal separation and recovery. Green Chemistry, 24(5), 1895-1929.

3 Smith, E. L., Abbott, A. P., & Ryder, K. S. (2014). Deep eutectic solvents (DESs) and their applications. Chemical reviews, 114(21), 11060-11082. https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas

4 https://www.oecd.org/content/dam/oecd/en/publications/reports/2015/02/material-resources-productivity-and-the-environment_g1g27386/9789264190504-en.pdf

5 https://iwaponline.com/jwrd/article/13/2/134/94168/Recovery-of-precious-metals-from-processed

6 Phogat, P., Kumar, S., & Wan, M. (2025). A scientometrics study of advancing sustainable metal recovery from e-waste: processes, challenges, and future directions. RSC Sustainability.

7 https://www.azomining.com/News.aspx?newsID=18339

8 https://www.gminsights.com/industry-analysis/precious-metals-e-waste-recovery-market

9 https://www.alliedmarketresearch.com/precious-metals-e-waste-recovery-market-A31390

10 https://scholar.google.de

11 https://www.mdpi.com/2673-4079/1/3/16

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