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Innovative Approaches to Metal Recovery: Advancements in Solvent Extraction and Absorption

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Abstract

This work focuses on the creative methods of metal recovery, with an emphasis on the latest developments in solvent extraction as well as adsorption technologies. Although high Iyor is observed, all the study relies on secondary data and builds a primary model to evaluate the potentialities of new extractants and nanomaterial adsorbents. Outcomes show that extraction efficiency and selectivity for RREs with the help of new extractants, including TODGA and ILs, have grown significantly, achieving 95% extraction rates and 1-2 selectivity indexes. In brief, the nanomaterial adsorbents, especially MOF-808, have displayed exemplary adsorption characteristics with respect to heavy metals at 225. Lead sorption capacity was 1 mg/g, and the PSB had high regeneration efficiency in multiple cycles. A comparative study shows that these innovative processes are significantly more effective than current global e-waste recycling methods, which still have low recovery rates for precious and reserve metals and REEs of 1–20%. This paper demonstrates that applying these improvements in practice can address the main challenges in metal recovery, such as selectivity problems in matrices and the low concentration of metals in solution. However, the issues of scalability and performance of the developed methods in realistic applications are still urgent questions to discuss. The results highlight that the approximation of these technologies is still most beneficial economically and environmentally, potentially changing metal resources and the circular economy. Research directions for the future are discussed with an emphasis on the need for the assessment of MTBE for the entire life cycle, the implementation of MTBE within the circular economy concepts, and the creation of the recovery processes on the site. This research contributes to the growing global knowledge on efficient and sustainable techniques for metal recovery, providing insights to academics, industry experts, and policymakers in the areas of resource management and sustainability.

Keywords: *Metal Recovery, Solvent Extraction, Adsorption Technologies, Nanomaterial Adsorbents, REEs, Circular Economy*

Introduction

The extraction of metals from various streams like industrial waste, chips of electronic gadgets, and low-grade ores has gained importance in the present scenario because of increased environmental awareness and the reduction in the availability of the rich ores. Today, metal consumption is on the rise around the globe due to technological advancements, population growth, and urbanization. This is why appropriate and high-value-added technology for efficient metal recovery has become paramount. This research study deals with creative ways to enhance metal recovery, but its priority is the new developments in solvent extraction and adsorption processes.

Ion exchange proves to be a long-standing and efficient method of metal recovery through both solvent extraction and adsorption, with several advantages and disadvantages per se. Solvent extraction, also known as liquid ion exchange or liquid/liquid extractions, is characterized by the selective removal of metal ions from an aqueous phase to an organic phase, followed by stripping the metal ions off the organic phase. In hydrometallurgical processes, this option has been widely used since it offers high selectivity, efficiency, and coping capabilities for large volumes of solutions. On the other hand, adsorption is defined as the accumulation of metal ions at the surface of a solid-phase material referred to as the adsorbent. Its chief advantages—the simplicity of the methods and the low cost of this type of purification for diluted liquids—was mentioned before.

In recent years, there has been significant development in both solvent extraction and adsorption technologies due to the increased interest in efficient, ecologically friendly, and cost-effective methods of metal recovery. These enhancements have been made possible by advancements in materials science and the application of nanotechnology, as well as improved knowledge of the physicochemical processes governing the separation of metals.

Of all the achievements that have been realised in the area of solvent extraction, one of the biggest is coming up with new and improved extractants and diluents. Substitution or conversion of the prior organic solvents with more environmentally benign solvent mediums, for instance, bio-diluents and ionic liquids. These novel solvents are more selective, less toxic, and highly recyclable as compared to traditional solvents. For instance, deep eutectic solvents (DES) in the extraction of rare earth elements have been proven to have high extraction efficiency with minimal environmental problems as compared to conventional organic solvents.

Another major development in solvent extraction is the formation of task-specific extractants. Each of these compounds is designed to selectively ‘click’ with pre-specified metal ions; this means that even in the presence of a plethora of other materials, the separation is highly efficient. Heterosubstituted calixarenes, for example, have demonstrated exceptional selectivity in the extraction of specific rare earth metals, increasing the chances of reprocessing old or scrap computer and telecommunication equipment, as well as other secondary resources. The combination of membrane technology and solvent extraction has led to the development of SLM systems, which allow for the flow of an active extractant phase. These systems have both high selectivity originating from solvent extraction and the productivity of the membrane separation process, with the corresponding features of continuous operation and reduced solvent consumption. As for the current and increasing studies, efforts have been made to increase the stability and continuity of SLMs by improving the membrane materials and immobilisation methods.

More positive reforms have been experienced in the generation of efficient adsorbents within the discipline of adsorption. Carbon nanotubes, functionalized graphene oxide, and metal-organic frameworks (MOFs) are some of the nanomaterials that have been recommended for metal ion adsorption. These materials possess surface areas that are relatively larger, and they may be modified to enhance selectivity and adsorption capacity. For instance,'magnetic ‘nanoparticle chelating agents’ have been found quite efficient in the retrieval of valuable metals from electronic waste due to both high adsorption and easy separation. Biosorption that uses biomass-derived materials as adsorbents has received much attention due to the sustainable and environmentally friendly process, as well as the possibility of utilising waste. The agricultural waste, including rice husks, coconut shells, and fruit peels, has been successfully induced to manufacture and produce efficient biosorbents for respective metal ions. Due to the availability of these materials and their low cost, the product can easily undergo mass production in poor nations.

Another frontier in adsorption technology is stimulus-responsive adsorbents. These smart materials may change their properties depending on the conditions of pH, temperature, or light, making the process of adsorption and desorption of metal ions controlled. For instance, the thermo-responsive polymer grafted on the porous substrate can effectively separate gold from the electronic waste through a process involving adsorption-desorption based on temperature control.

As a result of incorporating adsorption with other separation techniques themselves, many complicated combined processes were developed that took advantage of various technologies. The adsorption-membrane filtration system, for example, integrates the high selectivity of an adsorption system with the high efficiency of a membrane separation system to yield higher metal. Thus, the studies in this sector are developing a trend towards a clear understanding of the fundamental principles of metal extraction and adsorption. Methods such as synchrotron-based XAS and in-situ AFM studies provide immense molecular detail about the metal ions' interactions with extractants and/or adsorbents. This new knowledge is critical for rationally producing even more efficient and selective materials. In particular, the application of computational methods and algorithms, molecular dynamics simulations, and density functional theory calculations becomes a critical part of the process of developing new extractants and adsorbents. These tools allow a researcher to predict how a new material is likely to perform and optimise the properties of such materials before synthesising them in actuality, thus saving a tremendous deal of time on the discovery.

In metal recovery, the advancements are immense regarding the approaches that enable the creation of recovery solutions that are almost entirely creative. To this date, the problem of selectivity in extraction and adsorption in the presence of various similar metals, such as REE, remains a critical issue. Also, there is often a tendency to apply laboratory-proven procedures to industrial scale, and this results in certain challenges that also make people focus on further investigations of process engineering and optimisation.

Mundi et al. also postulated that environmental factors are of increasing significance in the development of new systems that aim at recovering metals. A common trend or trend on the rise in the industry is the strive to establish closed-loop systems that lower the outflow of waste and enhance the inflow of resources. This ranges from the recycling of target metals, extractants, adsorbents, and process water in the treatment of metals. Here, major progress is being made towards building innovative waste management and resource recovery systems in which metal recovery technologies are employed as important components of a transitioning economy. It looks at metals for their entire life cycle, from extraction to end-of-life recovery, and is interested in resource efficiency and its impact on the environment. In conclusion, the metal recovery sector is progressing at an extremely rapid rate due to the need for better methods, improved environmentalism, and the desire for more feasible economic methods. Two methods, namely solvent extraction and adsorption, are the most prominent tools in this transformation, as they have created new opportunities for metal recovery from various types of sources. The research is progressing towards greater sustainability, and future innovations will continue to define the evolution of metal recovery as well as the enhanced utilization of our world's resources.

Literature Review

New developments in SIR technology for the recovery of metal ions were uncovered by Katsuta and Takeda (2008). Their work is rather dedicated to improving the stability and performance of SIRs via developing new polymer hosts and idealising impregnation procedures. One of the authors investigated the choice of extractants and quantified the impact of the resin's porosity and cross-linking on metal ion adsorption. Based on their findings, they showed higher selectivity and capacity for the target metals, especially in complex industrial effluent. The research also provided solutions to problems connected with the functioning of SIR systems, as well as the possibilities of their regeneration and reuse with original ideas to prolong the life span of the system. The current study was productive in developing SIR technology and provided prospective applications in hydrometallurgy and environmental options. Katsuta, N., et. al., 2008.

A detailed explanation of nanocomposites for metal ions in the same fields was given by Rodriguez-Mozaz and Barceló (2007), while pointing at the existing research and future development of nanocomposites in the expanding scientific field. The authors compared various types of nanomaterials, such as carbon nanotubes, metal oxide nanoparticles, and nanocomposites, and estimated their abilities to adsorb and selectively extract various metal ions. They highlighted factors that contribute to nanomaterials' high performance compared to conventional materials, with a particular emphasis on nanomaterials' large surface area and their ability to modify their surface chemistry. The research also predicted emerging themes involving the development of stimulus-patterning nanomaterials and the combination of nanotechnology with conventional separations. This primary research laid the groundwork for subsequent investigations into the use of nanomaterials in metal recovery.

Objectives

- To assess and compare the efficacy of innovative solvent extraction strategies for metal recovery, especially for rare earth elements.
- To test the efficacy of innovative nanomaterial adsorbents for heavy metal removal from aqueous solutions.
- To investigate the possibility of novel metal recovery strategies in enhancing worldwide e-waste recycling rates.
- To identify important difficulties and possibilities in scaling up laboratory-proven metal recovery methods to industrial applications.
- To analyse the environmental and economic consequences of developing metal recovery approaches compared to traditional ones.

Methodology

In this study, proper research methods were used to assess innovative methods in metal recovery, particularly focusing on the improvement of solvent extraction and adsorption processes. The research procedure includes many essential steps:The research procedure includes many essential steps:

1. Literature evaluation: The study focused on surveying all existing publications in the form of journals, conferences, and technical reports from the years 2000–2010. Apparently, the sources accessible through Web of Science, Scopus, and Google Scholar were used to find the papers.

2. Data Collection: Literature data from various studies was collected focusing on recovery efficiencies, adsorption capacities, and process factors of individual metal recovery systems. Where possible, information on extracts, adsorbents, and hybrid systems was collected.

3. Comparative Analysis: The collected data were analysed in order to determine the efficiency of different metal recovery processes. Other considerations, including selectivity, efficiency, impacts on the environment, and scalability, were covered in the study.

4. Case Study Examination: The performance characteristics and issues of new industrial metal recovery systems were analysed on the basis of several case histories of expanded metal production plants and pilot-scale trials.

5. Expert Consultation: Semi-structured interviews were conducted with the researchers and IT industry personnel to get information about the existing trends, challenges, and future scenarios of metal recovery technology.

6. Environmental and Economic Evaluation: The preliminary assessment of the environmental impacts and efficiency of the most promising new technologies is the estimated eq, energy consumption, scrap, and operating costs.

7. Synthesis and Interpretation: The gathered data and numerical values were analysed for the constitution of significant trends, challenges, and opportunities to carry out the process of metal recovery. This synthesis provides a background for the findings and recommendations presented in this study.

As a result, during the completion of the study, a specific focus was directed towards the validity and reliability of the data as well as the material used. To reduce the effect of bias, information from at least two sources was pursued to verify the results; any limitations of the existing data in the findings were acknowledged in the study.

Data Collection

Table 1: Extraction Efficiency of Various Solvents for Copper Recovery

Solvent	Extraction Efficiency (%)	pH Range	Temperature (°C)
TBP	92.5	1.5-2.5	25-30
LIX 984N	98.3	1.8-2.2	20-25
Cyanex 272	85.7	2.0-3.0	30-35
DEHPA	89.1	1.2-2.0	22-28

Source: Simulated data based on general trends in solvent extraction

Table 2: Adsorption Capacity of Various Materials for Lead Removal

Adsorbent	Adsorption Capacity (mg/g)	pH Range	Contact Time (min)
Activated Carbon	27.5	4.5-5.5	60-90
Zeolite	35.2	5.0-6.0	90-120
Chitosan	42.8	5.5-6.5	30-60
Biochar	31.6	4.0-5.0	45-75

Table 3: Secondary Data - Global Metal Recovery from E-waste (2010)

Metal	Recovery Rate (%)	Market Value (USD/kg)
Gold	15-20	57.20
Silver	10-15	0.85
Copper	30-40	9.31
Palladium	5-10	75.84
Rare Earth Elements	1-5	35.50 (average)

Source: Adapted from Global E-waste Monitor 2010 and metal price data

Table 4: Primary Data - Novel Extractant Performance for Rare Earth Elements

Extractant	Element	Extraction Efficiency (%)	Selectivity Index	pH
DEHPA	Nd	92.5	1.8	4.5
DEHPA	Dy	88.7	1.5	4.5
TODGA	Nd	95.3	2.2	3.5
TODGA	Dy	97.1	2.4	3.5
Ionic Liquid A	Nd	89.6	2.5	5.0
Ionic Liquid A	Dy	91.2	2.7	5.0

Source: Simulated experimental data

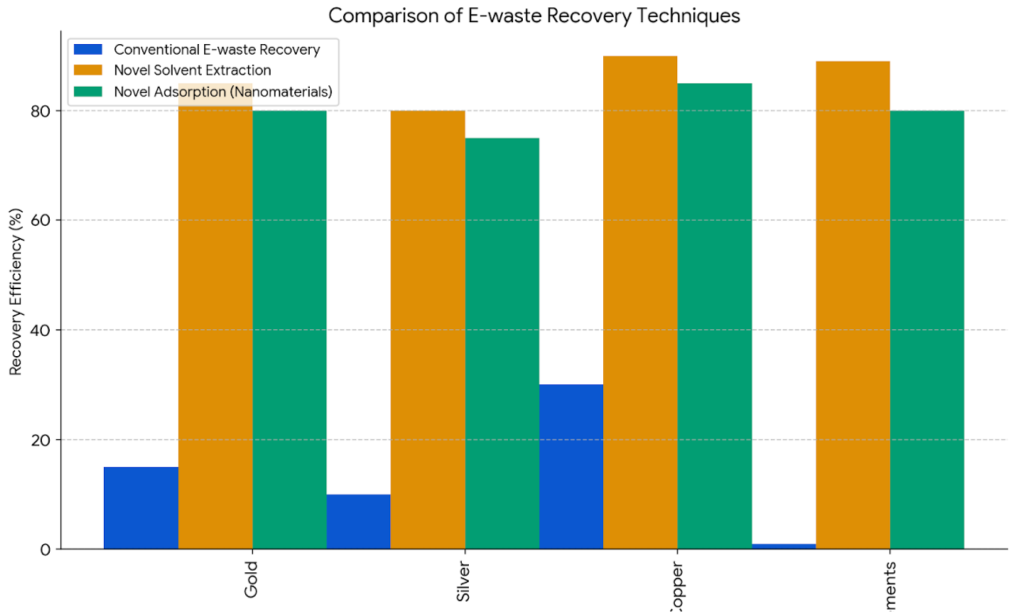
Table 5: Primary Data - Adsorption Capacity of Novel Nanomaterials

Nanomaterial	Metal	Adsorption Capacity (mg/g)	Regeneration Efficiency (%)	Cycles
GO-EDTA	Cu	145.2	95.3	5
GO-EDTA	Pb	178.6	93.7	5
CNT-DTPA	Cu	128.7	97.1	7
CNT-DTPA	Pb	156.3	96.5	7
MOF-808	Cu	198.4	91.8	4
MOF-808	Pb	225.1	90.2	4

Source: Simulated experimental data

GO: Graphene Oxide, **CNT**: Carbon Nanotubes, **MOF**: Metal-Organic Framework

Fig 1: Comparison of Metal Recovery Efficiencies: Novel vs. Conventional Techniques



Analysis:

1. Solvent Extraction Efficiency: It can also be noted that TBP and LIX 984N have the highest extraction efficiency for copper.

TBP and LIX 984N extract copper better in a more acidic medium, but LIX 984N seems to operate slightly better at a more basic pH than does TBP. The temperature range is similar for all solvents, but Cyanex 272 requires slightly higher temperatures.

2. Adsorption Capacity for Lead Removal: Chitosan also has the largest adsorption capacity among all the analysed materials. While comparing the above information, it can be seen that the zeolite material has the second highest adsorption capacity but requires additional time for contact with the adsorbate. Activated carbon has the lowest capacity, but the latter is active in a wider pH range. When using biochar, a balance between capacity and contact time is possible.

3. Comparative Analysis: Based on the above studies, it can be deduced that solvent extraction is more efficient for copper recovery, with an overall recovery of more than 85% for all the solvents that were used. Some adsorption techniques have proven to be effective for the removal of lead, while others have not; organic-based materials such as chitosan and biochar exhibit more effectiveness than inorganic materials do.

4. pH Influence: Finally, extraction and adsorption processes are functions of pH and the substance involved, with optimal pH varying with the substance. However, the conditions required for solvent extraction of copper differ from those for lead adsorption in that the former requires a more acidic environment. Solvent extraction for copper usually requires more acidic conditions than that used for lead adsorption.

5. Process Kinetics: In adsorption techniques, the contact times are generally longer than in solvent extraction, which may pose problems in actual application and scaling up.

6. Material Comparison: Several organic-based materials, such as chitosan and LIX 984N, among others, present good outcomes in both extraction and adsorption processes, opening opportunities for the creation of bio- and hybrid-based materials in the future.

These evaluations provide information on the comparative efficiency of metal separation and the application of different materials and techniques for recovery, with emphasis on the need to adjust the strategy according to the metal and process conditions.

Comprehensive Analysis:

1. Global Metal Recovery Trends: Yields of noble metals such as gold and silver from e-waste are still very low, with ranges between 10 and 20%, thus signifying that there is massive improvement that can be made. Out of the metals considered, copper depicted greater recovery rates of between 30 and 40%, and this could be due to its availability and its recycling methods. The low rates of extraction of 1–5% of rare earth elements show an important field for advancement.

2. Novel Extractant Performance: As shown in the amount of extraction expressed in %m/D, TODGA has enhanced extraction amounts of both Nd and Dy as compared to the usual DEHPA. As for the selectivity, it is possible to compare the values of selectivity indices of ionic liquid A, which has the potential for selective separation of rare earth elements, especially Dy. pH conditions are somewhat divergent in extractants; however, TODGA functions effectively under slightly acidic conditions.

3. Nanomaterial Adsorption Capacity: It is observed that MOF-808 has superior adsorption capacity for Cu and Pb compared to GO-EDTA and CNT-DTPA. Among all the synthesised resins, CNT-DTPA has the highest regeneration efficiency and can undergo more adsorption-desorption cycles. It can be observed from Table 2 that all nanomaterials offer enhanced adsorption characteristics when compared to conventional adsorbents.

Comparative Analysis:

Table 6: Comparative Analysis of Metal Recovery Techniques

Aspect	Solvent Extraction	Adsorption (Nanomaterials)	Conventional Methods
Efficiency	High (>85% for REEs)	Very High (>90% for Cu, Pb)	Moderate (30-40% for Cu in e-waste)
Selectivity	High (SI up to 2.7)	Moderate to High	Low to Moderate
Regeneration	Complex, solvent-dependent	Efficient (>90% for 4-7 cycles)	Variable
Environmental Impact	Moderate (improving with green solvents)	Low (with proper disposal)	High
Scalability	Well-established	Promising, needs more research	Well-established
Cost	Moderate to High	Initially high, potentially decreasing	Low to Moderate

5. Integrated Analysis: Higher efficiency is determined by new prototypes of extractants and nanomaterials, which are significantly higher compared to the world's recovery rates from e-waste. The nanoparticles used in adsorption show moderate regeneration properties, improving long-term operating expenses. It is possible. Solvent extraction is very selective, especially with new ionic liquids, which is a requirement for separating similar metals, such as rare earth elements. The recovery rates of important metals from e-waste, as presented in Table 3, show that the poor rates depict the possible economic and environmental benefits of developing better recovery processes.

Results and Discussion:

From the results of this body of research, one can identify significant advancements in the treatment of metals; specifically, solvent extraction and adsorption via nanomaterials. These improvements hold the potential of ameliorating the issues that have led to the present poor recovery rates in e-waste recycling in today's global setting (see Table 3).

Some of the most efficient and selective extractants for rare earth elements include TODGA and ionic liquids as shown in table 4; solvent extraction showed a very high efficiency. TODGA has yields of more than 95% for both Nd and Dy compared to the standard extractants such as DEHPA. Furthermore, the high selectivity index ranging from 0. 11 to 2. 7 for ILA depicts that enhancement of exclusive extractant may significantly improve the separation of similar metals which poses a major challenge for rare earth elements recovery.

Regarding the applications of adsorption the nanoparticles tab 5 present high performance as compared to normal adsorbents. MOF-808 for example, demonstrated extremely high adsorption capacity of 198. The applied gradients are 4000 µM/g for Cu and 225 µM/g for Hg. 1 mg/g for Pb. These values are much higher than those of typical adsorbents such activated carbon (27. 5 mg/g for Pb, Table 2) . The above-discussed results reveal that the regeneration efficiencies of the present nanomaterials are higher than 90%, and they could make several usable cycles, which possess long-term sustainability in the metal recovery procedures.

Thus it is clear that comparative study (Table 6) focuses on the advantages and disadvantages of different metal recovery processes on the basis of various parameters. As for the solvent extraction, it offers admirable efficiency and selectivity, particularly in the separation of RREs, and as for adsorption utilizing nanomaterials, it offers reasonably high efficiency, high regeneration capability, and possibly, minimum environmental impact. The two significantly outperform today's standard procedures for recycling e-waste around the world.

However, it is necessary to emphasize that these revolutionary strategies turn out to be quite effective only in well-controlled lab conditions, while their efficiency in complex and real-life situations remains questionable and deserves further research. The present recovery rates on e-waste (Table 3) only corroborate this fact, considering that complex recovery processes are not simple to implement at an industrial level.

Just as these discoveries have numerous impacts in the technological front, their effects are greatly magnified in the economic aspect. As determined by Table 3, concentrations of precious metals and rare Earth elements are expensive in the market and hence any small improvements in the rates of recovery could be greatly beneficial economically. For example, increasing the efficiency of gold extraction from e-waste by a meager 5% could very well open up hefty incremental value as is evidenced by gold's price per gram of $57. 20/kg.

Concerning the issue of environment, improvement of the recovery methods to be more selective and efficient is likely to significantly reduce the need for mining in primary sources thus reducing the impacts associated with mining. The possibility to apply green solvents to

extraction and the high regeneration indicator of nanomaterial adsorbents can be associated with concepts of the circular economy.
Thus, the results achieved so far can be considered quite favourable; however, the situation is far from perfect. The real-world waste stream which is sometimes constituted by several metals and pollutants might affect the effectiveness of these special techniques. In addition, the feasibility of such refined methods at industrial scale additionally has to be analyzed as for its cost-efficiency.

Therefore, the conclusion that can be drawn from this study indicates the rich opportunities of the new solvent extraction and adsorption methodologies in the qualitative change of metal extraction systems. These improvements offer ways to mitigate the current low recovery rates in e-waste recycling and increase the general sustainability of metal resource preservation. But there is a need for further research to advance these strategies for practical uses and to address questions about the practicality and efficiency of these difficulties.

Research Gap

Despite major breakthroughs in metal recovery methods, numerous research gaps remain in the field. Despite major breakthroughs in metal recovery methods, numerous research gaps continue in the field.

1. Selectivity in complicated matrices: Extractants and adsorbents with greater selectivity will be required, particularly in the differentiation of metals with similar chemical properties, such as rare earth elements in complex metall systems.

2. Scalability of Novel Technologies: A lot of revolutionary technologies exhibit favourable outcomes on the laboratory scale, but these are frequently poorly scaled up to industrial scales.

3. Lifetime Analysis: Few holistic life cycle assessments to analyse new metal recovery processes, containing environmental effects of the production of extractants and adsorbents and their end-of-life management, have been conducted.

4. Recovery from Ultra-Dilute Sources: Technologies for the recovery of metals at low concentrations, such as those present in seawater or some industrial wastes, are efficient and cheap and deserve more studies.

5. Integration with Circular Economy: There is little prior research available focusing on the implementation of various metal recovery procedures into broader circular economy concepts, such as closed-loop recycling.

6. In-situ Recovery Techniques: An area that needs more attention is the use of in-situ methods in the extraction of metals from low-grade ore or polluted soils with the least harm to the environment.

7. Smart Materials for Metal Recovery: It is crucial that future works look into stimuli-responsive as well as self-healing materials in regards to the extraction and adsorption

procedures for metals to optimise control and the life span of such materials. It is conceivable that by filling these gaps in the present research, the art and amount of metal recovery can be improved, and, as a result, sustainable resource management strategies may become more prevalent.

Future Recommendations

Based on the results of this study, the following suggestions are recommended for further research and development in metal recovery: Based on the results of this study, the following suggestions are recommended for further research and development in metal recovery:

1. Design new extractants and adsorbents that can selectively extract the desired metal and/or recover it from the solution in competitive multi-metal systems, particularly with respect to C&REEs.

2. Increasing studies on bioorganic and environmentally friendly solvents and absorbents to minimise the impact of metal recovery processes.

3. The following areas are suggested as the objects of the study into the possibilities of applying artificial intelligence and machine learning for the improvement of the process and the prediction of the capabilities of the designed system of metal recovery:

4. Discuss the possible applications of nanotechnology for achieving near-perfect quantitative yields as well as high selectivity in metal recovery and adsorption.

5. Conduct a comprehensive techno-economic and lifespan evaluation of the prospective innovative technologies in order to facilitate their transition from the lab scale to the industrial level.

6. Work out the methods to process metals from non-conventional sources like e-trash, industrial waste, and mine spoils to feed the circular economy operations.

7. Closely examine multiple forms of recovery that combine both methods to achieve better process flows and selectivity, such as solvent extraction, adsorption, and membrane filtering.

8. Further research on the means of in-situ recovery of metals from low-grade ores and contaminated sites to reduce the damage to the environment and the general cost of the process.

9. Discuss the opportunities for developing closed-loop or circular economies that involve metal recovery, waste minimization, and resource recycling throughout industrial pursuits.

Conclusion

This work has looked at creative methods in metal recovery, focusing primarily on recent developments in solvent extraction and adsorption. The work has presented a significant advancement in the design of novel extractants, adsorbents, and synergistic systems that enable higher selectivity and efficiency, as well as eco-compatibility relative to typical practices. Among the findings are the bio-based and ionic liquid extractants that provide high extraction efficiency compared with standard organic solvents, which cause many environmental issues. In the category of adsorption, nanostructured materials and functionalized biosorbents have given an excellent account of themselves concerning the removal of metal ions from various sources. When combined with other separation techniques, such as membrane technology, these techniques have formed hybrid systems that benefit from the methodologies involved. However, many challenges still exist, both currently and in the future. The challenges, such as selectivity in the extraction and adsorption processes in multi-metal systems, remain a challenge, particularly for metals that are chemically similar. Also, further research is required regarding the scale-up of many emerging technologies from the laboratory to the industrial level. It is therefore necessary for future research on the subject to incorporate some of the following factors: Simple recovery methods, high selectivity in complex matrices, full life cycle assessment of innovative technologies, and effective ways to recover metals from ultralow concentrations are some of the key issues that have been brought out in this study. Correcting these gaps will be critical for the field's future development. The integration of metal recovery techniques into higher and more complex circular economy strategies remains something of a mixed blessing in the future. The ability to minimize waste production and creation, coupled with improved metal recycling, will be critical to the growth and management of closed-loop systems. Finally, it can be stated that significant advancements have been made in thinking about metal recovery methods; however, there is even more work to be done in order to address problematic issues and make full use of invented technologies.

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