

REVIEW

From Cobalt to Kaolin: Molecular Signatures and Resource Recovery Pathways in Blue Porcelain Manufacturing Wastewater

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ABSTRACT

Manufacturing blue porcelain produces wastewater containing more cobalt, kaolin, silicates, and organic additives, which is a threat to the environment, as well as a resource recovery opportunity. This review summarizes existing information on the molecular composition of said effluents with a particular focus on cobalt speciation, mineral particle properties, and their interaction with organic ligands. Methods such as ICP-MS, XRD, SEM/TEM, and spectroscopy types offer important information concerning the behavior of metals and clays that will be used in designing targeted recovery operations. The most important methods of resource recovery, such as chemical precipitation, adsorption, electrochemical extraction, and physical separation of kaolin, are critically assessed, and emphasis is placed on integrated multi-stage technologies that maximize efficiency and the quality of a material. The environmental considerations, regulatory issues, and life-cycle are elaborated in order to put recovery strategies in the framework of sustainable manufacturing. The review highlights the possibility of integrating molecular-level knowledge and practical recovery technologies in making blue porcelain wastewater into a source of high-value products. Connecting analytical characterization, treatment procedures, and industrial application, this work offers a baseline of practices of the circular economy in the production of ceramics and lays down the direction of further research into the creation of sustainable and resource-efficient processes.

Keywords: Blue Porcelain Wastewater; Cobalt Recovery; Kaolin Reuse; Molecular Characterization; Circular Economy

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1. Introduction

Blue porcelain with its fine cobalt-blue decorations and transparent body is a masterpiece of ceramic arts, the history of which dates back several centuries^[1]. In addition to its cultural and aesthetic value, blue porcelain is a highly chemically intense technology, which requires the use of cobalt pigments, kaolin clays, silica, feldspar fluxes, and other organic additives^[2]. Although these are necessary in reaching the desired color, gloss, and mechanical properties, the materials result in complex wastewater streams in the process of manufacturing^[3]. **Figure 1** summarizes the key stages of production and the wastewater sources of these levels and indicates that the effluents consist of a combination of dissolved metals, suspended minerals, and organic residues that are highly hazardous to the environment. Among them, cobalt and kaolin are the most important ones: cobalt is a transition metal and a rather precious and even dangerous element, and kaolin is one of the major mineral fractions that could be used again if appropriately extracted^[4,5]. Although the production of ceramics has been practiced over the decades, the environment remains in bits on the molecu-

lar composition of these effluents and the process of ensuring that these effluents are simultaneously safe to the environment and the resources can be recovered.

Historically, studies of ceramic wastewater have been conducted on a large-scale basis in terms of traditional physicochemical variables like pH, total suspended solids, and chemical oxygen demand (COD)^[6]. Although these measures are practical toward the regulation compliance base, they do not reflect the molecular-based complexity of the porcelain effluents. Most recent developments in methods of analysis, such as inductively coupled plasma mass spectrometry (ICP-MS), high-performance liquid chromatography (HPLC), X-ray diffraction (XRD), and advanced electron microscopy, can now easily identify and quantitatively determine both inorganic and organic constituents^[7]. It is these developments that form a molecular level of understanding of these interactions of particular elements, e.g., cobalt, with the colloidal and dissolved mineral phases of kaolin and silica in the generation of wastewater. It is important to note that these molecular signatures can be used not only to reduce the environmental risks but also to allow the recovery of high-value materials, currently lost in effluent streams.

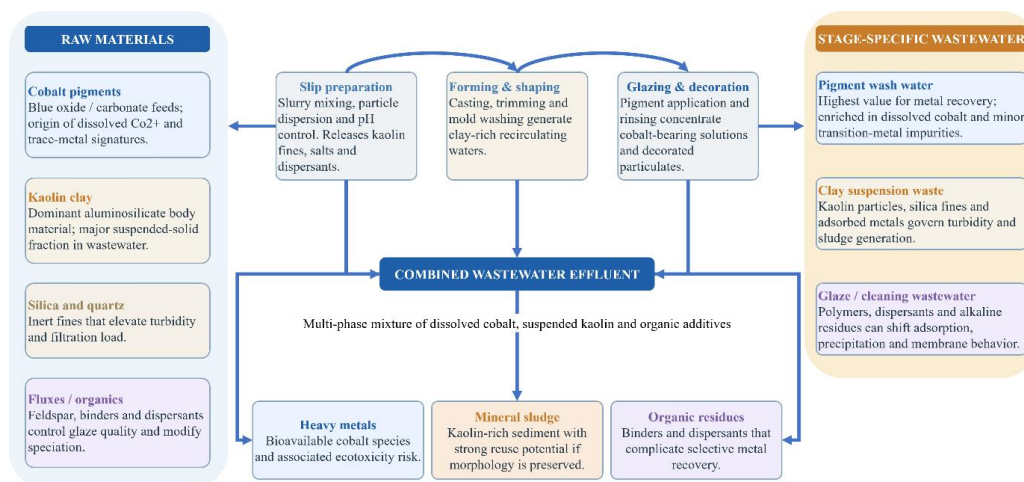


Figure 1. Schematic overview of blue porcelain manufacturing stages and associated wastewater generation points. The diagram highlights the primary raw materials (cobalt pigments, kaolin, silica, and fluxes), major processing steps, and the resulting release of metal ions, suspended minerals, and organic additives into wastewater streams.

The uniqueness of the review is that it concentrates on both the molecular characterization of blue porcelain wastewater, as well as the resource recovery techniques that could reuse these effluents in terms of value as second raw materials^[8]. Although earlier research has been done on either the environmental toxicity of cobalt or the physical

recovery of kaolin, very few have combined molecular-level understanding and practical recovery pathways^[9]. This review has demonstrated that particular chemical species and structural patterns are associated with their amenability to recovery, which provides opportunities to develop a circular approach to porcelain manufacturing - transforming wastew-

ater into one of the resources. Specifically, the discovery of molecular fingerprints offers a logical foundation on which a selective separation process is to be designed to enhance the efficiency and sustainability^[10]. This review brings together molecular-level speciation analysis and dual pathway design for recovery of both metals and clay from ceramic wastewater treatment, rather than focusing on conventional bulk parameters as done in previous reviews, or on metal recovery alone or clay recovery alone. Specifically, we (i) relate cobalt coordination chemistry with selective precipitation/adsorption strategies, (ii) relate kaolin particle morphology and surface charge to physical separation efficiency, and (iii) study the competitive interactions between dissolved metals and suspended minerals that determine the integrated treatment outcomes, which is not included in the existing literature.

In addition, the review attempts to discuss the interdisciplinary issues of this discipline. Cobalt recovery of the ceramic wastewater, as an example, cannot be achieved by mere chemical separation without knowledge of the coordination environment, solubility under different pH, and with the colloidal kaolin^[11]. At the same time, the recovery of kaolin requires the maintenance of its particle morphology and mineral integrity to retain its reuse in the ceramic formulations^[12]. This review, compiled from research based on materials science, environmental chemistry, and industrial process engineering, is a comprehensive outline of how future studies can be carried out by providing direction to academic research and the application process in industrial settings.

Lastly, the focus on the principles of sustainability and the circular economy is an indication of the bigger tendency in industrial production: the transition from the consumption of resources on a linear basis to a regenerative approach. Cobalt recovery is not only a remedy to environmental pollution but also a limitation on mining, which is an important factor to consider when considering the strategic value of cobalt in electronics and energy technologies^[13]. On the

same note, reclaiming kaolin will lead to efficiency in the resources and will reduce the cost of production^[14]. This review provides a new point of view that links the basic science with the applied industrial practice by placing these recovery strategies in the framework of a molecular perception of wastewater structure.

Overall, this review covers three complementary aims, namely (i) to comprehensively define the molecular footprint of blue porcelain wastewater, pinpointing essential inorganic and organic resources; (ii) to assess the existing and prospective resource recovery strategies behind cobalt, kaolin, and other minerals^[13]; and (iii) to present an overall scheme of developing sustainable and economically viable production of blue porcelain^[15]. Through the lens of molecular-level understanding and pragmatic recovery, this paper presents a basis for the creation of next-generation wastewater management methods in the ceramic sector, which is a major milestone in the quest to achieve environmentally sustainable and resource-efficient production methods.

2. Composition of Blue Porcelain Manufacturing Wastewater

The effluent produced as a result of the blue porcelain manufacturing process is a very complex wastewater, which has both inorganic and organic components, due to the complexity of the manufacturing process^[16]. Poorly processed by all the industries compared to traditional industrial effluents, porcelain wastewater combines all the raw materials used in various production phases, such as preparing the slip, glazing, decoration, and kiln processes. Knowing its composition is not only important in the assessment of environmental risk but also in the establishment of a chance to recover resources, especially in the form of high-value resources like cobalt and kaolin. The common constituents and concentration levels observed in blue porcelain wastewater have been summarized in **Table 1**.

Table 1. Representative inorganic and organic constituents of blue porcelain manufacturing wastewater, including their typical concentration ranges and environmental implications.

Component	Typical Concentration Range	Physical/Chemical Form	Environmental/Treatment Implication
Cobalt (Co ²⁺)	0.5–20 mg/L	Dissolved/complexed	Toxic, target for recovery
Kaolin	50–500 mg/L	Suspended particles	Sedimentation potential, reusable
Silica (SiO ₂)	10–200 mg/L	Particulate/dissolved	Influences turbidity, recovery via sedimentation
Feldspar/Fluxes	5–50 mg/L	Particulate	Minor mineral fraction, recoverable
Organic additives	1–50 mg/L	Polymers, deflocculants	Complex metals, affect adsorption/recovery

2.1. Inorganic Constituents

The most salient inorganic marker in blue porcelain wastewater is cobalt, which is obtained as a result of the cobalt oxide or carbonate dyes that are applied to give the material its characteristic blue color^[17]. Its level is very diverse with pigment loading, dissolution characteristics, and process efficacy, and can be found with levels as low as traces to a few milligrams per liter in industrial effluents. Speciation of cobalt is also an important aspect to consider since it can be present as dissolved ions (Co^{2+}) and also as particulate-bound cobalt metal complexes with clays and organic molecules. The pH, redox conditions, and the presence of chelating agents in wastewater greatly affect the bioavailability and mobility of cobalt and, therefore, the molecule-based characterization is necessary not only in the toxicity determination but also in the selective recovery^[18].

Another major constituent of the effluent is kaolin, the major clay mineral in porcelain bodies^[19]. Kaolin, in contrast to cobalt, is in the suspended solid phase, and particle size distribution is determined by milling and sedimentation, as well as filtration processes. Its existence in wastewater affects the physical characteristics of effluent, like turbidity and rheology, as well as the chemical interaction between the surfaces of metals and minerals^[20]. Other silicate minerals, feldspar fluxes, and quartz may also be present in trace levels, and this affects the crystallinity and adsorption capacity of the particulate phase. Critical assessment reveals that the interaction of these mineral portions and dissolved metal ions may impede or promote the recovery of metals, according to the kind of treatment scheme used.

2.2. Organic Constituents

Organic compounds present in the blue porcelain wastewater are fewer in number than inorganic species; however, they have a large impact on the process performance and behaviour of the environment^[16]. These are residual binders, deflocculants, and additives to regulate the slip viscosity, as well as by-products during the firing or glazing processes. Most of these organics have functional groups that are able to form complexes with metal ions, hence modifying their solubility and transportation. An example is polyacrylic acid-based deflocculants known to bind cobalt ions, which lowers the concentrations of free ions but may make it diffi-

cult to recover them by precipitation or adsorption^[21]. The organics are also very process-specific in how they are complexed, and their concentration may be influenced by the formulation, temperature, and residence time, thus requiring special analysis methods.

2.3. Variability across Production Stages

Blue porcelain wastewater does not have a homogeneous composition, and instead, it is systematically distributed at the production stages. Preparation of the slip produces effluents with a high concentration of suspended kaolin and dissolved fluxes, and glazing and decoration stages add to the concentration of cobalt and other metal pigments. The process of post-firing washing can add to the amount of soluble species, such as alkaline residues and washed-out silicates^[22]. There may be significant temporal and spatial variability, too, between a single facility, and traditional bulk chemical analysis may obscure important information about metal speciation or particle morphology. Comparative analyses have shown that facilities that use closed-loop water systems have a tendency to accumulate metals as well as clay particles with time, which results in the generation of effluents that are chemically and physically different from those of the open-system operations. This type of variability highlights the significance of characterizing the process of recovery at the molecular level to develop efficient recovery strategies that will be resistant to changes in the wastewater composition^[23].

2.4. Critical Insights and Implications for Recovery

The blue porcelain wastewater is complex in nature and poses challenges or opportunities. On the one hand, the presence of metals and suspended minerals also makes it difficult to use the conventional approach of the treatment since adsorption, precipitation, or filtration-based ones can be affected by other interactions and colloidal stability^[24]. Conversely, clear molecular signatures, e.g., patterns of cobalt speciation and mineral surface features, give a solid rationale for the targeted recovery approaches^[25]. Indicatively, the selective desorption of cobalt on kaolin particles can be informed by the identification of that particle, whereas the size of the sedimentation or flotation process can be optimized by the size distribution of the particles. Moreover, inorganic

and organic characterization are also integrated to provide a predictive model of the assessment of the treatment efficiency, which allows formulating processes that recover the precious metals and, at the same time, keep the kaolin intact to be reused in the ceramic formulations.

Overall, chemical analysis of blue porcelain wastewater is a multi-component system that is constantly changing and depends on raw materials, process design, and operational practice. To solve the sophisticated interplay that determines environmental influence and resource recovery potential, both molecular and particulate analyses are necessary to comprehend this very complex relationship. Through the combination of thorough characterization and process-specific understanding, one can go beyond traditional effluent management to an approach that converts the wastewater into a source of high-value products and preconditions the development of sustainable and circular production of blue porcelain^[26,27].

3. Molecular Signatures and Analytical Approaches

The molecular makeup of a blue porcelain wastewater is the key to environmental assessment and recovery of resources^[28]. This multidimensional interaction of dissolved metals, mineral particles, and organic additives forms distinct molecular signatures in which the raw materials and the manufacturing processes are reflected^[29]. Such signatures do not just unravel the chemical condition and speciation of the important elements like cobalt, but also form the basis of selective separation and recovery schemes. The developments in the field of analytical chemistry in the last 20 years have made it possible to characterize more and more accurately, providing new data on the interactions between inorganic and organic components. The principal analytical techniques used to identify these molecular signatures are summarized in **Table 2**.

Table 2. Comparison of commonly used analytical techniques for identifying metal ions, mineral phases, and organic compounds in porcelain wastewater.

Technique	Target Component	Information Provided	Advantages	Limitations
ICP-MS	Metals (Co, Ni, Fe)	Total concentration, trace detection	High sensitivity	Limited speciation info
XRD	Kaolin, Silicates	Crystal structure, phase ID	Non-destructive, mineral-specific	Requires solids, limited particle info
SEM/TEM	Mineral particles	Morphology, size, aggregation	High-resolution imaging	Time-consuming, small sample volume
FTIR/Raman	Organics, metal-organic complexes	Functional groups, chemical bonding	Non-destructive, identifies organics	Semi-quantitative, overlapping bands
XAS	Metals (Co speciation)	Oxidation state, coordination environment	Molecular-level insight	Requires synchrotron access

3.1. Inorganic Molecular Signatures

As the main coloring agent in blue porcelain, cobalt is one of the major molecular markers^[30]. It specializes in wastewater under different conditions based on its pH, redox conditions, and presence of complexing ligands. The chemical behavior of free Co^{2+} , cobalt hydroxides, and organo-cobalt complexes is different, as they affect their solubility, mobility, and recoverability. Inductively coupled plasma mass spectrometry (ICP-MS) and atomic absorption spectroscopy (AAS) are among the most commonly used spectroscopic methods to help determine total cobalt concentrations in a very sensitive manner^[31]. Nevertheless, these procedures are not sufficient to distinguish soluble ions from those that are bound by particles. X-ray absorption spectroscopy (XAS) and synchrotron-based spectroscopies have been developed to overcome these differences and give detailed information on oxidation state, coordination environment, and bonding interactions. The capacity to characterize cobalt

species on a molecular basis is essential in the development of selective recovery processes that will achieve the highest possible extraction rates and reduce the occurrence of secondary contamination.

Other silicate minerals, such as kaolin, though found mostly in the form of colloidal or particulate matter, also add to the molecular signature of the wastewater^[32]. The X-ray diffraction and Fourier-transform infrared spectroscopy (FTIR) can be used to characterize mineral crystallinity, polymorphism, and surface functional groups, which are determining factors of adsorption and metal attachment^[33]. The scanning and transmission electron microscopy (SEM and TEM) give further understanding of the morphology and aggregation of particles and directly impact the efficiency of sedimentation, flotation, and filtration^[34]. Interestingly enough, when cobalt ions interact with kaolin surfaces, it is usually seen that surface-bound complexes are formed, and these may either hinder or promote recovery depending on the conditions under which the treatment is being conducted.

The combination of crystallographic, morphological, and chemical studies allows mapping of the molecular landscape of inorganic components that is used in the rational design of separation strategies.

3.2. Organic Molecular Signatures

Although organic additives are found in smaller amounts in blue porcelain wastewater in comparison to inorganic additives, their effects are disproportionate when it comes to the interactions of chemicals. Cobalt ions may be chelated by polymers, surfactants, and binders, changing colloidal stability and altering adsorption patterns on clay surfaces^[35]. These organics can be identified and quantified by using high-performance liquid chromatography (HPLC) with mass spectrometry (MS), and structural information about polymer chains and functional groups can be obtained by using nuclear magnetic resonance (NMR) spectroscopy^[36]. The development of organometallic complexes between cobalt and organic ligands is of particular importance, since it affects toxicity, as well as recoverability. The behavior and prevalence of these complexes are therefore critical to understanding the development of integrated treatment approaches that would be able to be effective in the recovery of metal as well as organic removal.

3.3. Emerging Multi-Modal Approaches

The latest developments in analytical techniques have allowed the use of multi-modal characterization incorporating chemical, structural and morphological data and generating a multi-dimensional molecular profile of wastewater. The use of synchrotron X-ray fluorescence (XRF) mapping and laser ablation ICP-MS techniques has made it possible to analyse in a spatially resolved manner the pattern distribution of metals on particulate matter to identify heterogeneities in a manner that determines recovery potential^[37]. In the same way, the combination of FTIR or Raman spectroscopy with chemometric modeling will allow identifying the presence of slight interactions between organics and inorganics, which may not be detected using traditional bulk methods^[38]. These methods are especially useful in closed-loop systems, in which recycling and the build-up of metals and clays produce complicated and changing effluents. Multi-modal characterization is diagnostic

and predictive, showing the changes in molecules during processing on a molecular scale, thus providing the opportunity to develop specific recovery strategies that consider the dynamic chemistry of wastewater.

3.4. Critical Analysis and Implications for Recovery

Resource recovery: the fine molecular description of blue porcelain wastewater has a far-reaching impact. Recovery of particular species of cobalt can be done by selective recovery via precipitation, adsorption, or electrochemical recovery, whereas knowledge of the kaolin surface chemistry guides sedimentation, flotation, or membrane-based recovery^[39]. Feedback between organics and inorganics also further suggests the significance of combined treatment methods; e.g., polymer-bound cobalt may need pH modification or chemical replacement before traditional recovery^[5]. More importantly, the understanding of the molecular processes is also applied to optimization of the processes: with the help of correlating particular signatures to the operational parameters, manufacturers are able to vary pigment loading, slurry formulation, or wastewater treatment to obtain higher recovery yields and lower environmental impact.

To sum up, blue porcelain wastewater is a complex and interesting characteristic that can be utilized to map the composition of raw materials and the impact of the process. The tools and methods of analysis have offered a transition between basic chemistry and useful recovery methods by providing resolution in the counting and identification of these species in ways never before seen. Through these molecular understanding techniques, strategies of recovery can be developed logically to maximize the extraction of valuable metals, maintain the integrity of clay minerals, and bring the industry into more sustainable and circular manufacturing^[29].

4. Environmental Impacts and Regulatory Framework

The wastewater of blue porcelain manufacturing poses a complex environmental problem because of its heterogeneous nature in terms of metals, minerals, and organics. Cobalt is one of the most hazardous elements, as it is toxic at high levels, whereas suspended kaolin and other silicate

particles affect the sedimentation, turbidity, and ecosystem interactions^[40,41]. The environmental impact of these constituents, and the legal context that regulates the release of effluents, are all that is needed to develop efficient treatment and recovery measures.

4.1. Toxicological Concerns of Cobalt and Associated Metals

The Cobalt in blue porcelain waste is mostly found as Co^{2+} or free on the surface as a complex with clays and organics. Soluble cobalt is considerably bioavailable and even low levels may be very hazardous to aquatic life, leading to oxidative stress, interruption in enzymatic pathways, and build-up in the body tissues^[40]. Prolonged exposure to cobalt in human beings has been associated with respiratory, cardiovascular, and skin diseases, whereas acute toxicity may be caused by direct contact or oral consumption of cobalt-contaminated water^[42]. Additional trace metals, including nickel, manganese, and iron, could be included, either as impurities in the pigments or as part of the raw materials, and could also add to the possible ecotoxicity of the effluent^[43]. The relationship between metals and organic ligands has the potential to change bioavailability, to reduce or increase toxicity based on the strength of complexation, solubility, and redox status. These molecular-level interactions show that chemical characterization on the molecular level is essential to the correct assessment of the risks posed by the environment.

4.2. Impact of Suspended Solids and Mineral Particles

Porcelain wastewater solids are composed of a significant percentage of kaolin and other mineral particulates. These particles may affect the physical and ecological processes, although they are chemically inert in comparison with dissolved metals. The turbidity may decrease the penetration of light in water bodies, which impacts the photosynthetic organisms and alters the food webs^[44,45]. Small particles of pollutants may accumulate at the bottom of the sediments, forming permanent hotspots of contamination over time, and have the ability to adsorb metals and organics, which are later leached with changing environmental conditions. The size of the particles, their surface charge, and the mineralogy

of the kaolin determine the rate of sedimentation and the recovery efficiency of the flocculation or flotation recovery process. Thus, the amount of minerals is not only a resource that can be recovered but also an important aspect to reduce the impact on the environment^[46].

4.3. Regulatory Landscape and Discharge Standards

Different regulatory frameworks for wastewater of the ceramic industry differ depending on the regions and are more inclined towards both chemical and biological parameters. The discharge standards normally have the limits of total dissolved solids, pH, COD, and concentrations of certain metals, including cobalt, nickel, and lead^[21]. Indicatively, the European Union Industrial Emissions Directive establishes strict limits on heavy metals in effluent materials of non-ferrous metal processes, which might be extended to those of cobalt-contaminated ceramic wastewaters. National standards of ceramic wastewater (GB 21900-2008) in China establish maximum permissible content of total suspended solids, heavy metals, and alkalinity, showing concern for environmental protection and the health concerns of the population. Adherence to such regulations commonly involves pre-treatment, such as pH adjustment, flocculation, or filtration, before discharge. Notably, regulatory requirements can shape the structure of recovery procedures: the necessity to decrease the amount of cobalt and decrease the level of toxicants in the environment to the established standards makes selective mining not only quite profitable but also a legal necessity^[16].

4.4. Life-Cycle and Sustainability Considerations

It is necessary to view the environmental impact of blue porcelain wastewater through the lens of a life-cycle view. From the extraction of the raw material to the glazing and kiln processes, at each step, there is the addition of metals, organics, and minerals to the total load of effluents. Recycling water in closed-loop systems, which have become popular in the new plants, concentrates metals and clays with time, forming effluents that are enriched chemically but easier to recover. As per life-cycle assessment (LCA) research, an effective reuse of cobalt and kaolin can tremendously help

decrease the environmental footprints, reducing the usage of resources and the chances of contamination^[47]. The combination of molecular-level characterization and LCA allows marking important points of control, on which interventions, perhaps by changing the composition of pigments, changing the pH of the wastewater, or modifying sedimentation procedures, would also help maximize the recovery and minimize the environmental release^[48].

4.5. Critical Insights

The porcelain blue wastewater environment is regulated by a complicated association among chemical speciation, particulate matter, and working practices. The toxicity does not only rely on the cumulative concentration of metal but also on the specification of cobalt, metal-organic complex, and even the association of particles^[49]. On the same note, the potential hazard of suspended kaolin is contingent upon size distribution, mineral composition, and adsorption of contaminants. The regulatory standards do offer the required restraints, but in most cases, they do not factor in these molecular-level interactions, which points out a disparity between policy and science. To narrow this divide, accurate analytical characterization, predictive modeling, and compliance and resource recovery treatment should be used. This kind of approach allows not only for protecting the environment but also for converting wastewater into a valuable product and reducing it to a liability, which is in line with the principles of the circular economy.

5. Resource Recovery Pathways

Blue porcelain wastewater has a complicated and complex structure that introduces challenges and opportunities in the recovery of resources. The fact that high-value metals (mainly cobalt) and mineral fractions like kaolin are present makes a strong argument to convert effluents into a source

of secondary raw materials^[5,13]. New developments in separation and treatment technologies, based on characterization of molecules at the molecular level, have made it possible to adopt selective recovery approaches that are highly cost-effective and environmentally friendly. This section is a critical assessment of the main avenues of the recovery of metals and minerals, as well as integrated strategies that ensure the highest level of resource efficiency.

5.1. Recovery of Cobalt and Other Metals

Cobalt recovery is a high priority because it has an economic value, and it is toxic to the environment. Conventional methods are based on chemical precipitation, usually as hydroxides, sulfides, or carbonates, with or without pH manipulation or the use of precipitating agents^[11]. Such techniques can work well on a large scale, but have the drawback of co-precipitation with other metals and the creation of fine colloidal fractions that are hard to separate. Alternative methods have been identified as adsorption-based, such as the use of functionalized resins, bio-sorbents, or nanomaterials^[50]. Based on selective molecular associations between the cobalt ions and the surface ligands, the methods use this to selectively bind even when other metals are present. Electrochemical recovery is highly pure, and recovery can be achieved, but it needs great attention to electrodeposition and electrolysis parameters. **Table 3** shows a comparison of the significant cobalt recovery methods and their operational characteristics. More importantly, the type of recovery procedure should be based on considerations of cobalt speciation because the soluble Co^{2+} ions, organo-complexed cobalt, and particle-bound species have varying reactivity and recoverability. It has also been shown that pre-treatment procedures, including pH stabilization, chelator displacement, or controlled oxidation, can be used to increase the recovery efficiency of cobalt complexed, or as particles, to a state that can be extracted.

Table 3. Comparative assessment of cobalt recovery technologies used for ceramic wastewater treatment, including recovery efficiency, advantages, and technical challenges.

Recovery Method	Targeted Co Species	Recovery Efficiency	Advantages	Challenges
Chemical precipitation	Co^{2+} , partially complexed	70–90%	Simple, cost-effective	Co-precipitation, fine colloids
Adsorption (resins/bio-sorbents)	Dissolved/organo-complexed	80–95%	Selective, scalable	Adsorbent regeneration, sensitivity to organics
Electrochemical extraction	Co^{2+}	85–98%	High purity, selective	Energy-intensive, requires pre-treatment
Ion exchange	Co^{2+}	75–90%	High selectivity	Limited capacity, sensitivity to competing ions

5.2. Recovery and Reuse of Kaolin and Mineral Fractions

As the major constituent of porcelain wastewater in the form of particulate matter, kaolin is both an environmental issue and a source of valuable resources^[5]. Physical separation techniques are applied in recovery strategies and include sedimentation, centrifugation, and flotation^[51]. The key recovery methods of kaolin and the basic features of their functioning are described in **Table 4**. The parameters that are considered to affect the separation efficiency are particle size distribution, colloidal stability, and surface charge. Flocculation or coagulation chemical conditioning may be

used to increase the rate of sedimentation and allow recovery of kaolin of high purity. Notably, care should be taken to preserve the morphology and crystallinity of the particles to retain the suitability of the material when it comes to reusing it in the production of ceramics. In addition to kaolin, small quantities of silicate minerals and flux remnants may also be reclaimed and recycled into porcelain recipes, eliminating the need for raw materials. Recent studies have pointed out the possibility of combining the recovery of minerals with the recovery of metals, and thus use the different adsorption of cobalt and other metals on the surfaces of the clay to allow a sequential recovery process.

Table 4. Comparison of physical separation methods for kaolin recovery from porcelain wastewater and their implications for mineral reuse in ceramic production.

Recovery Method	Mechanism	Recovery Efficiency	Impact on Particle Morphology	Notes for Reuse
Sedimentation	Gravity-driven	60–80%	Minimal alteration	Suitable for slip formulations
Flotation	Surface property-based	70–90%	Maintains particle integrity	Requires conditioning, surfactants
Centrifugation	Density-based	80–95%	Slight compaction possible	High recovery, energy-intensive
Filtration	Physical separation	50–75%	Particle structure is mostly preserved	Limited by fine colloids

5.3. Integrated Treatment and Recovery Approaches

There is a growing trend towards using integrated methods involving the combination of chemical, physical, and biological treatments to recover the resource. The multi-stage systems can be used to remove suspended solids and kaolin at the same time, concentrating the metals in a smaller volume. High selectivity then follows with subsequent extraction of metals by chemical or electrochemical treatment. Alternative methods such as biosorption and bioleaching are also coming up as supplementary methods, especially when dealing with effluents that have complexed metals or organic substances. In one example, microorganisms that are used for metal-binding or engineered biofilms can selectively capture cobalt, whereas organic additives are broken down, making it easier to harvest the additives using chemicals. Molecular-level understanding of wastewater composition is useful because the design of such integrated systems can optimize successive stages of treatment and reduce the loss of useful materials^[52].

5.4. Industrial Case Studies and Practical Implementation

There are several pilot and full-scale implementations that show that resource recovery of blue porcelain manufac-

turing is feasible. When a facility uses closed-loop water systems, there is a tendency to accumulate increased cobalt and kaolin, which, with a combined sedimentation and adsorption process, can be easily extracted. Industrial operations have had electrochemical recovery units installed, which have attained purities of cobalt that can be further used in pigment. Equally, recovered kaolin has been reintroduced into slip formulations without causing much effect on the quality of the product. The analysis of these implementations has been critical; that is, recovery efficiency greatly relies on the upstream control of the process, especially in the control of pigment load, particle size distribution, and the content of organic additives. Real-time optimization with the help of molecular-level monitoring and process engineering can be used to minimize material losses and make sure it complies with the discharge requirements^[53,54].

5.5. Critical Insights and Future Directions

The blue porcelain wastewater recovery of resources demonstrates the prospects of the principles of the circular economy in manufacturing. Effective recovery intervention demands profound knowledge of the chemical and physical interactions between metals, minerals, and organics. Characterization on a molecular level allows the extraction process to be very selective and highly effective. The future studies

should be based on the enhancement of the scalability and cost-efficiency of combined recovery systems and the use of new materials as adsorbents or catalysts, and predictive modeling of wastewater composition-recovery performance relationships. Also, the combination of recovery with real-time monitoring and process feedback strategies will help

to promote continuous improvement and adaptive management, so that the blue porcelain production can be refocused on the sustainable and resource-efficient manufacturing process^[55]. The overall circular resource framework linking wastewater treatment with material reuse is illustrated in **Figure 2**.

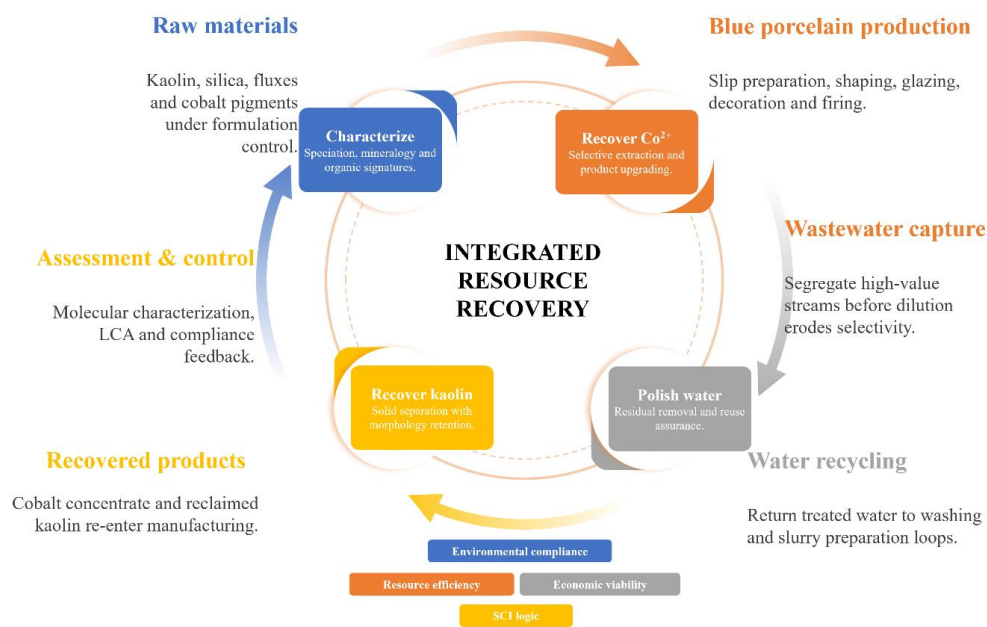


Figure 2. Circular economy model illustrating how molecular characterization and resource recovery technologies enable the recycling of cobalt pigments, kaolin minerals, and treated water back into porcelain manufacturing processes.

5.6. Research Gaps, Technical Challenges, and Future Directions

Although substantial progress has been made, there are still several research gaps. First, real-time monitoring of cobalt speciation in industrial processes is not yet possible, which limits adaptive process control. Secondly, the stability of the organo-cobalt complexes under varying pH and redox conditions is not well characterized, which makes the design of pre-treatment steps challenging. Third, there are no standard quality parameters for recovered kaolin suitable for reuse in ceramic applications, which makes it difficult for manufacturers to be certain.

The main technical challenges are: interference from organic deflocculant (20–40% decrease in precipitation efficiency), energy consumption in electrochemical extraction (0.5–2 kWh/m³), and fouling of membranes/adsorbents by fine clay particles. Future research should focus on: (i) the development of a low-cost sensor for cobalt speciation in the

field, (ii) the development of a selective chelating agent to remove organic ligands from cobalt, (iii) machine learning models predicting Cobalt recovery results from molecular fingerprints, and (iv) a comprehensive life cycle assessment of recovered cobalt against primary resources. Filling these gaps will shorten the path to transitioning from linear to circular porcelain production^[56–58].

6. Conclusion

The wastewater of blue porcelain production is a complicated mixture of dissolved metals, suspended minerals, and organic additives, with the most significant elements being cobalt and kaolin. This is a review that demonstrates the significance of molecular-level characterization in the deposition of how soluble metals, particulate minerals, and organic ligands interact, and that all of them influence both the impact on the environment and the chance of recovery. The recovery of cobalt can be best achieved by an integra-

tion of the understanding of metal speciation and binding mechanisms using chemical precipitation, adsorption, and electrochemical extraction methods, but kaolin recovery is based on the maintenance of particle morphology and mineral integrity through the use of the most effective physical separation processes. Multi-stage techniques, which are based on the combination of chemical, physical, and biological methods, have the most promising solutions to achieving the maximum material recovery and reducing environmental discharge. Life-cycle and regulatory frameworks reveal the need to make recovery goals and approaches consistent with both environmental compliance and the principles of the circular economy. Altogether, a combination of the extensive molecular knowledge and implementation of the recovery technologies can turn wastewater into a stream of resources. This holistic approach not only enhances sustainable and resource-efficient blue porcelain manufacturing but is a road map to expanded industrial wastewater management approaches, which combine environmental stewardship, material reuse, and economic sustainability.

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References

- [1] Colombari, P., Kırmızı, B., Simsek Franci, G., 2021. Cobalt and Associated Impurities in Blue (and Green) Glass, Glaze and Enamel: Relationships between Raw Materials, Processing, Composition, Phases and International Trade. *Minerals*. 11(6), 633. DOI: <https://doi.org/10.3390/min11060633>
- [2] Rapp, G., 2009. *Ceramic Raw Materials*. In *Archaeomineralogy*. Springer: Berlin/Heidelberg, Germany. pp. 183–200. DOI: https://doi.org/10.1007/978-3-540-78594-1_8
- [3] Martínez-García, C., Eliche-Quesada, D., Pérez-Villarejo, L., et al., 2012. Sludge valorization from wastewater treatment plant to its application in the ceramic industry. *Journal of Environmental Management*. 95, S343–S348. DOI: <https://doi.org/10.1016/j.jenvman.2011.06.016>
- [4] Johanson, P., 2008. *Cobalt*. The Rosen Publishing Group, Inc.: New York, NY, USA.
- [5] Oyewo, A.T., Adediji, W.O., Ajenikoko, K.O., et al., 2025. Enhancing Ceramic Material Properties through Kaolin Beneficiation: A Review. *Uniosun Journal of Engineering and Environmental Sciences*. 7(2). DOI: <https://doi.org/10.64980/ujees.v7i2.445>
- [6] Dinçer, A.R., Kargı, F., 2000. Characterization and biological treatment of ceramic industry wastewater. *Bioprocess Engineering*. 23(2), 209–212. DOI: <https://doi.org/10.1007/s004490000207>
- [7] Fisher, A., Goodall, P., Hinds, M.W., et al., 2004. Atomic spectrometry update. Industrial analysis: metals, chemicals and advanced materials. *Journal of Analytical Atomic Spectrometry*. 19(12), 1567–1595. DOI: <https://doi.org/10.1039/b416929h>
- [8] Shurygin, M., Guenther, C., Fuchs, S., et al., 2021. Effective treatment of the wastewater from ceramic industry using ceramic membranes. *Water Science and Technology*. 83(5), 1055–1071. DOI: <https://doi.org/10.2166/wst.2021.039>
- [9] Chen, M., Yang, T., Han, J., et al., 2023. The Application of Mineral Kaolinite for Environment Decontamination: A Review. *Catalysts*. 13(1), 123. DOI: <https://doi.org/10.3390/catal13010123>
- [10] Cai, C., Li, L., Guan, Y., et al., 2024. High-throughput computational screening and molecular fingerprint design of metal-organic framework adsorbents for separation of C3 components. *Giant*. 17, 100223. DOI: <https://doi.org/10.1016/j.giant.2023.100223>
- [11] Chandra, M., Yu, D., Tian, Q., et al., 2022. Recovery of Cobalt from Secondary Resources: A Comprehensive Review. *Mineral Processing and Extractive Metallurgy Review*. 43(6), 679–700. DOI: <https://doi.org/10.1080/08827508.2021.1916927>
- [12] Karhu, M., 2020. *Utilization of Mineral Side Streams in High Temperature Ceramic Materials [PhD Thesis]*.

- Tampere University: Tampere, Finland.
- [13] Mudd, G.M., Weng, Z., Jowitt, S.M., et al., 2013. Quantifying the recoverable resources of by-product metals: The case of cobalt. *Ore Geology Reviews*. 55, 87–98. DOI: <https://doi.org/10.1016/j.oregeorev.2013.04.010>
 - [14] Yu, L., Zhang, Y., Wang, H., et al., 2024. Enhancing the sustainable production of cost-effective ceramics with high strength using kaolin, sewage sludge and blast-furnace slag. *Chemical Engineering Journal*. 480, 148184. DOI: <https://doi.org/10.1016/j.cej.2023.148184>
 - [15] Settembre Blundo, D., García Muiña, F.E., Pini, M., et al., 2018. Lifecycle-oriented design of ceramic tiles in sustainable supply chains (SSCs). *Asia Pacific Journal of Innovation and Entrepreneurship*. 12(3), 323–337. DOI: <https://doi.org/10.1108/APJIE-06-2018-0039>
 - [16] Vințan, D.M., 2013. Monitoring of Porcelain Industry Wastewater Case Study: Sc Apulum Sa Alba Iulia. *Journal of Young Scientist*. 1, 149–158.
 - [17] Anaissi, F., Horsth, D., Dalastra, J., et al., 2020. Design, Synthesis, and Application of Colored Cobalt Pigments (Pink, Blue, Green). *Journal of the Brazilian Chemical Society*. 31(11), 2265–2273. DOI: <https://doi.org/10.21577/0103-5053.20200078>
 - [18] Awual, M.R., Hasan, M.M., Islam, A., et al., 2020. Optimization of an innovative composited material for effective monitoring and removal of cobalt(II) from wastewater. *Journal of Molecular Liquids*. 298, 112035. DOI: <https://doi.org/10.1016/j.molliq.2019.112035>
 - [19] Nwuzor, I., Chukwuneke, J.L., Nwanonenyi, S.C., et al., 2018. Modification and physiochemical characterization of kaolin clay for adsorption of pollutants from industrial paint effluent. *European Journal of Advances in Engineering and Technology*. 5(8), 609–620.
 - [20] Mustapha, S., Tijani, J.O., Ndamitso, M.M., et al., 2020. The role of kaolin and kaolin/ZnO nanoadsorbents in adsorption studies for tannery wastewater treatment. *Scientific Reports*. 10(1), 13068. DOI: <https://doi.org/10.1038/s41598-020-69808-z>
 - [21] Dobre, T., Isopencu, G.O., Bdaiwi Ahmed, S., et al., 2024. Heavy Metal Pollution and Solutions for Its Control: General Aspects with a Focus on Cobalt Removal and Recovery from Aqueous Systems. *ChemEngineering*. 8(6), 118. DOI: <https://doi.org/10.3390/chemengineering8060118>
 - [22] Edwards, H.G.M., 2018. Components of Porcelain Manufacture. In *Nantgarw and Swansea Porcelains*. Springer International Publishing: Cham, Switzerland. pp. 75–97. DOI: https://doi.org/10.1007/978-3-319-77631-6_4
 - [23] Zheng, M., Hu, Z., Liu, T., et al., 2024. Pathways to advanced resource recovery from sewage. *Nature Sustainability*. 7(11), 1395–1404. DOI: <https://doi.org/10.1038/s41893-024-01423-6>
 - [24] Ayach, J., El Malti, W., Duma, L., et al., 2024. Comparing Conventional and Advanced Approaches for Heavy Metal Removal in Wastewater Treatment: An In-Depth Review Emphasizing Filter-Based Strategies. *Polymers*. 16(14), 1959. DOI: <https://doi.org/10.3390/polym16141959>
 - [25] DuChanois, R.M., Cooper, N.J., Lee, B., et al., 2023. Prospects of metal recovery from wastewater and brine. *Nature Water*. 1(1), 37–46. DOI: <https://doi.org/10.1038/s44221-022-00006-z>
 - [26] Maponya, T.C., Makgopa, K., Somo, T.R., et al., 2022. Highlighting the Importance of Characterization Techniques Employed in Adsorption Using Metal–Organic Frameworks for Water Treatment. *Polymers*. 14(17), 3613. DOI: <https://doi.org/10.3390/polym14173613>
 - [27] Kathi, S., Singh, S., Yadav, R., et al., 2023. Wastewater and sludge valorisation: a novel approach for treatment and resource recovery to achieve circular economy concept. *Frontiers in Chemical Engineering*. 5, 1129783. DOI: <https://doi.org/10.3389/fceng.2023.1129783>
 - [28] Popa, M., Vintan, D., Roxana, B., et al., 2014. Study concerning the wastewater quality in the porcelain industry. *Journal of Environmental Protection and Ecology*. 15(1), 53–60.
 - [29] Staszak, K., Wieszczycka, K., 2023. Recovery of Metals from Wastewater—State-of-the-Art Solutions with the Support of Membrane Technology. *Membranes*. 13(1), 114. DOI: <https://doi.org/10.3390/membranes13010114>
 - [30] Jiang, X., Ma, Y., Chen, Y., et al., 2018. Raman analysis of cobalt blue pigment in blue and white porcelain: A reassessment. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*. 190, 61–67. DOI: <https://doi.org/10.1016/j.saa.2017.08.076>
 - [31] Guo, Y., Zhao, H., Han, Y., et al., 2017. Simultaneous spectrophotometric determination of trace copper, nickel, and cobalt ions in water samples using solid phase extraction coupled with partial least squares approaches. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*. 173, 532–536. DOI: <https://doi.org/10.1016/j.saa.2016.10.003>
 - [32] Xu, M., Wang, J., Wu, J., 2024. Recent advances of silicate materials for wastewater treatment: a review. *Materials Research Express*. 11(3), 032001. DOI: <https://doi.org/10.1088/2053-1591/ad2c63>
 - [33] Ali, A., Chiang, Y.W., Santos, R.M., 2022. X-ray Diffraction Techniques for Mineral Characterization: A Review for Engineers of the Fundamentals, Applications, and Research Directions. *Minerals*. 12(2), 205. DOI: <https://doi.org/10.3390/min12020205>
 - [34] Leppard, G.G., 2008. Nanoparticles in the Environment as Revealed by Transmission Electron Microscopy: Detection, Characterisation and Activities. *Current Nanoscience*. 4(3), 278–301. DOI: <https://doi.org/10.2174/157341308785161109>
 - [35] Svanedal, I., Eivazi, A., Norgren, M., et al., 2024. Ex-

- ploring the versatility of chelating surfactants: A review. *Current Opinion in Colloid & Interface Science*. 73, 101833. DOI: <https://doi.org/10.1016/j.cocis.2024.101833>
- [36] Levsen, K., 2000. Application of high-performance liquid chromatography coupled to nuclear magnetic resonance and high-performance liquid chromatography coupled to mass spectrometry to complex environmental samples. *TrAC Trends in Analytical Chemistry*. 19(1), 27–48. DOI: [https://doi.org/10.1016/S0165-9936\(99\)00178-8](https://doi.org/10.1016/S0165-9936(99)00178-8)
- [37] Carter, S., Clough, R., Fisher, A., et al., 2020. Atomic spectrometry update: review of advances in the analysis of metals, chemicals and materials. *Journal of Analytical Atomic Spectrometry*. 35(11), 2410–2474. DOI: <https://doi.org/10.1039/D0JA90067B>
- [38] Schumacher, W., Kühnert, M., Rösch, P., et al., 2011. Identification and classification of organic and inorganic components of particulate matter via Raman spectroscopy and chemometric approaches. *Journal of Raman Spectroscopy*. 42(3), 383–392. DOI: <https://doi.org/10.1002/jrs.2702>
- [39] Hua, Q., Guo, H., Wang, D., et al., 2022. A new strategy for selective recovery of low concentration cobalt ions from wastewater: Based on selective chelating precipitation-flotation process. *Journal of the Taiwan Institute of Chemical Engineers*. 141, 104605. DOI: <https://doi.org/10.1016/j.jtice.2022.104605>
- [40] Paustenbach, D.J., Tvermoes, B.E., Unice, K.M., et al., 2013. A review of the health hazards posed by cobalt. *Critical Reviews in Toxicology*. 43(4), 316–362. DOI: <https://doi.org/10.3109/10408444.2013.779633>
- [41] Schieber, J., Li, Z., Yawar, Z., et al., 2023. Kaolinite deposition from moving suspensions: The roles of flocculation, salinity, suspended sediment concentration and flow velocity/bed shear. *Sedimentology*. 70(1), 121–144. DOI: <https://doi.org/10.1111/sed.13034>
- [42] Linna, A., 2023. Effects of Cobalt Exposure on the Respiratory System and the Heart Among Cobalt Production Workers [PhD Thesis]. Tampere University: Tampere, Finland.
- [43] Sharma, M., Kant, R., Sharma, A.K., et al., 2025. Exploring the impact of heavy metals toxicity in the aquatic ecosystem. *International Journal of Energy and Water Resources*. 9(1), 267–280. DOI: <https://doi.org/10.1007/s42108-024-00284-1>
- [44] Boyd, C.E., 2020. Suspended Solids, Color, Turbidity, and Light. In *Water Quality*. Springer International Publishing: Cham, Switzerland. pp. 119–133. DOI: https://doi.org/10.1007/978-3-030-23335-8_6
- [45] Bilotta, G.S., Brazier, R.E., 2008. Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research*. 42(12), 2849–2861. DOI: <https://doi.org/10.1016/j.watres.2008.03.018>
- [46] Hao, X., Wang, X., Liu, R., et al., 2019. Environmental impacts of resource recovery from wastewater treatment plants. *Water Research*. 160, 268–277. DOI: <https://doi.org/10.1016/j.watres.2019.05.068>
- [47] Ungureanu, A., Sola, A., Neri, P., et al., 2025. Systematic life cycle assessment of cobalt-based blue ceramic pigments: evaluating CoAl₂O₄ and lower-cobalt alternatives. *Green Chemistry*. 27(41), 12946–12958. DOI: <https://doi.org/10.1039/D5GC02709H>
- [48] Lo Giudice, A., Ingrao, C., Clasadonte, M.T., et al., 2017. Life cycle assessment for highlighting environmental hotspots in the Sicilian traditional ceramic sector: the case of ornamental ceramic plates. *Journal of Cleaner Production*. 142, 225–239. DOI: <https://doi.org/10.1016/j.jclepro.2016.05.028>
- [49] Chen, Y., Xu, H., Shi, J., et al., 2025. Application of Metal-Organic Framework Composites. *ChemistryEurope*. 3(6), e202500078. DOI: <https://doi.org/10.1002/ceur.202500078>
- [50] Gupta, A., Sharma, V., Sharma, K., et al., 2021. A Review of Adsorbents for Heavy Metal Decontamination: Growing Approach to Wastewater Treatment. *Materials*. 14(16), 4702. DOI: <https://doi.org/10.3390/ma14164702>
- [51] Zhang, N.-N., Zhou, C.-C., Liu, C., et al., 2017. Effects of particle size on flotation parameters in the separation of diaspor and kaolinite. *Powder Technology*. 317, 253–263. DOI: <https://doi.org/10.1016/j.powtec.2017.04.049>
- [52] Maarof, H.I., Daud, W.M.A.W., Aroua, M.K., 2017. Recent trends in removal and recovery of heavy metals from wastewater by electrochemical technologies. *Reviews in Chemical Engineering*. 33(4), 359–386. DOI: <https://doi.org/10.1515/revce-2016-0021>
- [53] Wen, Y., Dong, L., Xu, J., et al., 2024. Molecular Insights into the Transformation of Dissolved Organic Matter in a Full-Scale Wastewater Treatment Plant. *ACS ES&T Water*. 4(9), 4228–4238. DOI: <https://doi.org/10.1021/acsestwater.4c00534>
- [54] Li, M., Li, Z., Fu, L., et al., 2024. Molecular-level insights into dissolved organic matter and its variations of the full-scale processes in a typical petrochemical wastewater treatment plant. *Water Research*. 261, 121990. DOI: <https://doi.org/10.1016/j.watres.2024.121990>
- [55] Fernandes, J., Ramisio, P.J., Puga, H., 2024. A Comprehensive Review on Various Phases of Wastewater Technologies: Trends and Future Perspectives. *Eng*. 5(4), 2633–2661. DOI: <https://doi.org/10.3390/eng5040138>
- [56] Chang, Y., Zhou, J., Yang, D., et al., 2025. Overcoming limitations in electrochemical water softening: A comprehensive analysis of key factors and recent technological advancements. *Separation and Purification Technology*. 354, 128971. DOI: <https://doi.org/10.1016/j.seppur.2024.128971>

- [57] Luo, J., Zhan, Z., Li, W., et al., 2025. Coupling adsorption and electrochemically mediated precipitation for enhanced water softening and antiscalant recovery. *Separation and Purification Technology*. 377, 134264. DOI: <https://doi.org/10.1016/j.seppur.2025.134264>
- [58] Yan, Z., Zhu, Z., Chang, H., et al., 2023. Integrated membrane electrochemical reactor-membrane distillation process for enhanced landfill leachate treatment. *Water Research*. 230, 119559. DOI: <https://doi.org/10.1016/j.watres.2022.119559>