International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 22s, 2025
https://theaspd.com/index.php

Advances in Electroplating Wastewater Treatment Technologies in Meeting Sustainable Development Goals

Waseem Ullah Khan[1], Sirajuddin Ahmed[2], Aftab Alam[3]
[1]University Polytechnic, Jamia Millia Islamia, New Delhi-110025, India
[2]Department of Civil Engineering, Jamia Millia Islamia, New Delhi-110025, India
[3]Maulana Azad National Urdu University, Hyderabad, India
*Corresponding Author: wkhan3@jmi.ac.in

ABSTRACT: *The electroplating and metal finishing industries play a pivotal role in the advancement of the manufacturing sector. Despite their economic and functional advantages such as reduced water usage and lower waste production these industries are major contributors to environmental pollution due to the release of toxic heavy metals and cyanide compounds. The low permissible limits of these pollutants make their removal critical for both ecosystem and human health protection. While conventional treatment methods like chemical precipitation, ion exchange, and reverse osmosis are commonly used, electrochemical techniques such as electrodialysis and electrocoagulation have emerged as efficient and sustainable alternatives. This paper reviews current treatment strategies, including physical, chemical, and electrochemical methods, with an emphasis on post-treatment and sludge management. It also discusses the alignment of these technologies with Sustainable Development Goals (SDGs), especially in the context of water reuse, zero liquid discharge, and environmental sustainability. The study aims to highlight industrial trends, environmental implications, and future prospects in advancing electroplating wastewater treatment technologies.*
Keywords:*Electrochemical methods; Electroplating industry effluents; Heavy metals; Wastewater treatment; Sustainable Development Goal.*

1. INTRODUCTION

In India, similar to many other industrial sectors, electroplating has a rich history and experienced significant growth after the country gained independence. However, it wasn't until 1976 when the first semi-automatic facility was established in Mumbai, marking a milestone in the sector's advancement. The adoption of modern electroplating techniques in India began in the early 1960s, and since then, the industry has experienced continuous expansion without encountering a recessionary phase. As per the 2007 Comprehensive Industry Document on Electroplating Industry (COINDS), there are currently over 600 automated plants operating nationwide, although official statistics are unavailable. Estimated figures suggest that the electroplating business generated Rs. 100 million in 1970. The government's import restrictions policy, implemented between 1970 and 1985, played a significant role in fueling the industry's rapid growth (International Metalworkers Federation, 2002). The electroplating sector expansion trajectory exhibited a consistent increase from 1980 to 2002, with a notable spike observed between 2002 and 2012. It is predicted that the value of the electroplating sector would reach 20 billion in 2012. As one of the vital sectors of the Indian economy, the metal plating industry generates millions of job opportunities.

Metal corrosion can be prevented or for aesthetic purposes, metal coatings are applied through electroplating by hydrolyzing metal (H. Kanematsu & D.M. Barry,2016). The electroplating sector plays a vital role in our modern community and way of life, contributing significantly to the economy by facilitating important projects. Various industries, including electronics, automotive, aerospace, and petrochemical sectors, utilize electroplating to manufacture a variety components (Liu et al., 2012). Electroplating proceedure primarily using electricity to dissolve deposit it onto a surface(Barry et al., 2016).This process relies on four main components: the anode, cathode, solution, and power source. The anode serves as the positively charged electrode in the circuit and consists of the metal that will form the plating. On the other hand, the cathode, also known as the substrate, is the part that needs to be plated and acts as the negatively charged electrode in the circuit. This process allows producers to reduce production costs since expensive metals are used to coat affordable materials like plastic or metal. To ensure efficiency, plating is often done by barrel or rack plating when multiple products are being plated. Currently, various surface finishing techniques are employed to strengthen and protect material surfaces.Electroless coatings is a process to chemically deposits coatings without the use of electric current (Muraliraja etal., 2023).Physical vapor deposition is a method of vaporizing the material to be deposited. The resulting vapor condenses onto a substrate's surface, creating thin coatings ranging from 0 to 20 micrometers in thickness (Dan ET AL., 2022). A process for deposition of material is chemical vapour deposition (CVD). through the interaction between a heated substrate and its surrounding atmosphere containing the vapor or gases constituting the coating material. CVD is used to deposit hard coatings such as carbides, nitrides, oxides, diamond, and diamond-like carbon (DLC) for wear resistance (Schalk et al., 2022).Other Surface Finishing Techniques are Galvanizing, Powder coatings, Diffusion coatings, Conversion coatings, Anodizing, Phosphate coatings, Chromate coatings, Thermal spraying.

Electroplating involves covering a ready surface of metal with a thin protective metallic coating using an electrochemical method. Some metals cannot coat the metal surface during this process. This bare metal exits the system with the sewage. Toxic metals may enter the aquatic food chain and harm the system if this waste water is dumped directly into a body of water that absorbs it. As a result, appropriate care must be received before discharge. Chrome and Lead are frequently used materials by plating industry. However, the rinse water used in conventional electroplating industries generates a significant amount of wastewater, leading to environmental concerns (Babu et al., 2009).

The high metal ion content in the wastewater exceeds the discharge limits set by the Ministry of Environment, making treatment necessary before release. If untreated wastewater containing toxic metals is directly discharged into bodies of water, it can get into the oceanic food web and harm the ecosystem (Khan et al., 2019).Lead and chromium are commonly used plating materials, and their release into clean water streams is limited to 0.1 ug/cm3 according to the Pollution Control Acts, Rules, and Notification),(CPCB),2006 (Alothman et al., 2013). Plating sludge, which contains valuable metals like chromium, nickel, and copper, is currently considered solid waste and disposed of in landfills. However, this disposal method negatively impacts the environment and habitats (Ahmad et al., 2020). When wastewater discharges combine with water bodies, they have significant consequences on the aquatic ecosystem, wildlife, and human health (Alsubih,et al., 2021). Recycling these heavy metals not only offers significant financial gains but also alleviates the burden on Effluent Treatment Plants (ETPs) (Raju et al., 2019). Some electroplating industries, particularly those using rare-earth metals like platinum, gold, and silver, generate effluent containing substantial quantities of these precious metals.Therefore, proper wastewater treatment is essential to remove heavy metals and recover these valuable resources for economic and environmental reasons. The electroplating industry has traditionally employed various wastewater treatment methods, but it is still considered a hazardous contaminating industry in India and is classified in the red group according to (Gayathri et al., 2021). As most electroplating businesses are small enterprises, they often lack the resources to upgrade their technology and manufacture environmentally friendly products (Moreira et al., 2020). Collective volume of effluent generated by many electroplating sectors amounts to approximately 1.5 MLD.

The wastewater released by these industries typically contains numerous composite components, some of which can be toxic or harmful to the environment in various ways. Many South Asian countries, in particular, continue to struggle with the problem of watercourse pollution, specifically the discharge of untreated electroplating effluents into municipal sewers (Nair et al., 2014). Therefore, it is crucial to address this issue promptly and give it the necessary attention when taking the ecosystem into account before allow to leave this wastewater. There are several affordable pre-treatment methods available that can adequately process the harmful effluent and ensure that its discharge into the environment does not cause any harm. The objective of this research is to evaluate and analyze advanced treatment technologies for electroplating wastewater, with a focus on electrochemical methods. It aims to compare traditional and modern techniques in terms of efficiency, sustainability, and alignment with environmental regulations. The study also seeks to explore the integration of Zero Liquid Discharge (ZLD) and water reuse practices to minimize ecological impact. Additionally, it examines the potential of these technologies in supporting the implementation of Sustainable Development Goals (SDGs).

2. Wastewater from electroplating industries

Over the past two decades, various pollutants such as wastewater, toxic elements, and contaminated natural compounds were discharged in the environment, particularly in developing countries, as a result of electroplating, metallurgical, mining, and power generation activities (Chen et al., 2013). Because of its chemical formation, negative atmospheric consiquences, with insufficient practical as well as legitimate guidelines for ecological discharge, the treatment of industrial electroplating effluents has become a significant concern since 1947 (Bankole et al., 2019). In the 1950s, The first method for treating such effluents was developed and introduced to the market around 1950.

Processes like electrolytic plating baths, electrolytic baths for treating metal surfaces, and galvanizing operations all contribute to the production of electroplating wastewater. Among chemical-intensive industries, the electroplating industry is considered one of the riskiest globally because of significant release of pollutants, containing toxic elements with other persistent harmful substances (Guan et al., 2020). Electroplating effluents may hold the combination between heavy elements, cyanide complexes, turbidity, total solids (TS),suspended solids (SS),biological oxygen demand (BOD), and chemical oxygen demand (COD).Electroplating industry effluents often exhibit intense coloration and high levels of inorganic impurities such as copper, chromium, iron, sodium, calcium, sulfates, phosphates, and phosphate nitrates. Approximately 29% of waste generated by the electroplating industry is considered toxic or hazardous, with concentrations of these toxic metal ions often exceeding acceptable limits. Proper treatment of surface finishing and coatings industry effluents is crucial to prevent further environmental damage before their discharge.

Effluents from the electroplating, tanning, mining, and steel sectors ditinguished by deadly cyanide, varying natural substance levels, extreme pH levels (high or low), as well as chromium,iron, nickel,copper, zinc and nitrogen content (Fu and Wang, 2011). Despite their small quantities, toxic elements are extremely hazardous to the atmosphere may cause various diseases in humans (Table 1). Due to their low solubility, heavy metals are not easily broken down in wastewater, resulting in their accumulation over time. The rinsing water used in metal plating, which accounts for approximately 20% of the chemicals used in salt baths, contributes significantly to the volume of wastewater generated in typical electroplating industries (Babu et al., 2009).

Table 1 : Effluents from the Electroplating Industry and Permissible Limits (Indian and WHO standard)

Parameter	**Toxicity / Health Effects**	**Typical Concentration in Effluent (mg/L)**	**WHO Limit (mg/L)**	**Indian Std. Limit (mg/L)**
Chromium (Cr^{6+})	Carcinogenic, damages respiratory tract, skin, kidneys	0.1–200	0.05	0.05
Copper (Cu)	Liver and kidney damage, gastrointestinal irritation	0.1–50	1	0.05
Nickel (Ni)	Skin dermatitis, lung fibrosis, respiratory cancer	0.5–80	0.2	-
Lead (Pb)	Neurotoxicity, affects kidneys and central nervous system	0.05–5	0.01	0.1
Zinc (Zn)	Nausea, vomiting, stomach cramps, immune system suppression	0.1–100	3	-
Cadmium (Cd)	Renal dysfunction, bone damage, carcinogenic	0.01–1	0.003	0.01
Arsenic (As)	Skin lesions, cancer, cardiovascular disease	0.01–0.5	0.01	0.05
Cyanide (CN^-)	Inhibits cellular respiration, extremely toxic in small amounts	0.1–20	-	0.2
Total Suspended Solids (TSS)	Clogs aquatic gills, reduces light penetration	50–3000	-	100
Oil and Grease	Reduces oxygen transfer in water, forms scum	10–50	-	10

Direct disposal of wastewater into natural water bodies poses serious risks to the aquatic ecosystem, while discharging it into sewers can compromise subsequent biological effluent treatment proceedure (Matis et al., 2004). Numerous natural and inorganic contminants exist ineffluent increases potential for surface, groundwater, and soil contamination (Dehghani et al., 2017; Khan et al., 2019). Electroplating effluents, despite their relatively small volume, contain substantial quantity of elements are challenging to treat (Oyaro et al., 2007).

Phytoremediation, which involves using plants to treat contaminated soil and water in an environmentally friendly manner, is one of the many remediation methods employed. Oceanic herbsserve as critical agent in the improvement of effluents generated through various industries by absorbing and storing trace and toxic elements.To safe guard the soil from harmful impacts of electroplating wastewater, current research focuses on identifying aquatic plants, including those capable of removing toxic metals such as hexavalent chromium, that are essential for improving these effluents (Murari and Lanka, 2022). The removal of 95.65% Nickel (Ni) and 61.10% chromium (Cr) is possible with vetiver grass (Nugroho et al., 2021).Sricter regulations and growing environmental awareness have also compelled industries to intensify their efforts in finding effective wastewater treatment technologies (Tehe et al., 2016). The successful treatment or elimination of these hazardous metals from effluents is crucial to address this issue. This research paper discuss various options avialble to treat the electroplating effluent.

3.Ttreatment methods for industrial waste water:

Industries face various challenges when it comes to minimizing pollutant release, managing water resources, and optimizing energy use. Consequently, several treatment techniques have been developed to ensure environmental protection. The most effective and reliable methods for reducing industrial wastewater comprises to, agglomeration and coagulation, membrane filtration, precipitation, electroflotation, ion exchange, electrocoagulation, advanced oxidation process, adsorption, electrooxidation, and electrodialysis processes (Yadav et al., 2021). These techniques employ powerfull technologies to remove the pollutants through effluent by utilizing their inhibitory properties. Table 2 is the Comparison of Conventional and Electrochemical Methods for Electroplating Wastewater Treatment. Specific protocols are employed to address the release of water-polluting substances, and these processes are protected by various patents (Kang, 2003; Chongwu Guo, 2020). When selecting a most suitable treatment technique, several factors need to be considered, such as effectiveness, productiveness, versatility, as well as protection. Nevertheless, it's important to remember tha for wastewater with metal ion concentrations below 1100 mg/L, many treatment methods prove to be inefficient and costly (Al-Qodah and AlShannag, 2017). The optimal removal technique should be quick, efficient, cost-effective, and environmentally friendly.

Table:2 Comparison of Conventional and Electrochemical Methods for Electroplating Wastewater Treatment

Aspect	**Conventional Methods**	**Electrochemical Methods**
Examples	Chemical precipitation, ion exchange, adsorption, membrane filtration	Electrocoagulation, electro-oxidation, electro-Fenton, electro-flotation
Chemical Usage	High (e.g., coagulants, pH adjusters, oxidants)	Low or negligible (uses electric current instead of chemicals)
Sludge Generation	High; requires further treatment and disposal	Low; sludge is less voluminous and often easier to handle
Treatment Efficiency	Moderate; less effective for complex or low-concentration pollutants	High; can achieve >99% removal for metals and COD
Process Complexity	Often requires multiple stages and dosing controls	Simpler design; process can be automated
Secondary Pollution	Risk of residual chemicals or excess sludge disposal	Minimal; process does not produce harmful by-products
Energy Consumption	Low to moderate	Moderate to high, but often offset by improved efficiency
Capital/Operating Cost	Lower initial cost, but higher ongoing chemical and sludge management costs	Higher initial cost, but lower chemical and long-term operating costs
Recovery Potential	Limited (metal recovery often not feasible)	High potential for metal recovery from sludge and treated water
Flexibility and Scalability	Moderate; less adaptable to variable loads or contaminants	High; can be tailored to specific pollutants or effluent characteristics
Environmental Impact	Higher due to chemicals and sludge disposal issues	Lower; clean and green process, especially suitable for ZLD and water reuse schemes

3.1 Coagulation and flocculation methods

The process of Coagulation involves suspended and indissoluble molecules come together to form larger aggregates through the addition of coagulants. By neutralizing the repelling interactions among nanosized molecules, coagulation destabilizes the particles, as noted by Kurniawan et al. (2006), Fu and Wang (2011), Oropeza-Guzman et al.(2014). Coagulation and flocculation techniques have gained wide recognition as efficiently treating both home as well as factory effluents and this method has exceptional efficacy in eliminating suspended particles (Barbosa et al., 2018; Peters and Mostafa, 2016).In traditional effluent treatment processes, coagulants like ferrous sulfate sodium aluminate, ,ferric chloride, aluminum sulfate, and others are frequently employed for neutralizing particle charges also help in removal of particulate contaminants from wastewater (Yadav et al., 2021).

Coagulation efficiently remove concentrated ions of metal ranging with100 mg at the lowest to 1000mg at the higest, particularly when the pH is between 11.0 and 11.5. It functions in a manner similar to chemical precipitation, where insoluble and dissolved particles combine with coagulation reagents in a specific volume, constitute sizeable clumps.Throughout flocculation proceedure, gentle mixing is employed to aid in the settling and formation of sedimentary flocs. Coagulation-flocculation methods are utilized to eliminate undissolved particles through wastewater, and effectiveness of separating suspended matter is influenced by factors like size of particle, appearance, as well as hardness. Similarly charged sun dissolve matter remain in water and repels one another. Flocculation-coagulation escalate collision of particle, balance charges on surface as well as promote the enlargement of flocs through deposition.

The negatively charged surface of suspended particles neutralizing by coagulants, resulting in the formation of small microflocs. Agitation disperses the coagulants, facilitating particle collisions and effective coagulation. Typically, one to three minutes of contact time is allowed in the high-speed mixing chamber. Flocculation generate the growth of size of particles, resulting in production of larger flakes called pin flakes. Floc exposure period varying between fifteen to twenty minutes, and blending speed is consistently reducing to avoid breaking apart the flocs. Coagulation techniques precipitate poorly soluble substances such as hydroxides, sulfides, and carbonates. Coagulation treatment enhances the elimination of agglomerated particles also increases the density of settled matters. Coagulation efficiency relies on various aspects, including the category as well as coagulant dosage used, pH, temperature, and other variables.

In effluent treatment procedure, chemical reagents or coagulants are commonly used and inorganic coagulants are one of these. Frequently used Inorganic coagulants that are comprises of ferric chloride ($FeCl3$), aluminium sulphate ($Al2(SO4)3$) as well as ferric sulphate ($Fe2(SO4)3$),along with their derivatives (Achak et al., 2019) Iron alum, used in the sedimentation phase of the coagulation process, generates a significant amount of sediment. Coagulation has been effective in treatment of elements like chromium, nickel, cadmium, and zinc (Bazrafshan et al., 2015; Hoek et al., 2016). Coagulation - Flocculation are successfulto eliminate the toxic elements heavy metals through wastewater. The coagulants market worldwide and flocculants is expected rise to approximately US$7 billion by 2025 (Flocculant & Coagulant Market - Forecast(2023 – 2028), highlighting the significance and high demand for this treatment technology. Natural coagulants are also gaining popularity as sustainable alternatives to inorganic and synthetic coagulants to meet sustainable development goals (Ang and Mohammad, 2020). However, the use of coagulants in this process leaves some effluents behind in industrial wastewater and generates sludge (Chang and Wang, 2007). Therefore, the combination of precipitation or random reduction with flocculation or coagulation is necessary in the wastewater treatment process. The coagulation-flocculation process offers advantages such as shorter settling times for suspended particles, improved sedimentation, drainage properties, bacterial deactivation, and increased sediment strength. However, the process also has drawbacks, including elevated cost of operation because of chemical usage and requirement of analysisto generated sediments for metal recovery (Kurniawan et al., 2006; Fu and Wang, 2011). Actual plating effluent that holds copper (Cu), nickel (Ni), and chromium (Cr) was treated using heat-inactivated cells of coagulants strain of Saccharomyces cerevisiae. which reduced polluents to the below permissible limit. Erdite/zeolite-bearing flocculant produced by sludge containing Fe, Al, Si was used to effectively treat the real electroplating wastewater containing Zn/Ni (Gao et al. 2023).

Sufficient progress is made in the development of biofloculent which found to be very efficient. Biofloculents are classified as extracellular metabolites flocculant, intracellular extract flocculant and bacteria flocculant.

3.2 Chemical precipitation technique

Because of well-developed methodology, chemical technique sextensively adopted with in plating sector with minimal expenditure requirements. The general process of chemical precipitation methods is described by (Chen et al. 2009a). Chemical treatment is considered the most effective method for treating electroplating wastewater, but it may not completely resolve the entire issue (Lu and Wu, 2020). Chemical precipitation engineering involves two main processes: sulphide precipitation and hydroxide precipitation. Zn, Cr, Cu, Mn, and Cd all can be removed through wastewater by chemical precipitation, as stated by(Bilal et al.2013). By reacting precipitating agents like sulphides with dissolved ions of metal or hydroxides, chemical precipitation creates insoluble metal precipitates (Kurniawan et al., 2006).

The solubility of ions of metal in effluentmay reduced via adjusting pH, and hydroxide precipitation is favored in many countries due to its convenience and utilise the cost-effective precipitating substance like lime as well as limestone. However, sulphide precipitation may result in higher metal removal (Fu and Wang, 2011). The separation of chemicals is employed for the purification of rare metals (Babel and del Mundo Dacera, 2006). Toxic elements treatment with hydrated oxide, cacium oxide, andsulphide, through chemical precipitating technique commonly applied for advanced electroplating sectors. This technique lowers pH to an optimal range, reducing the solubility of ions of metal present in wastewater. The advantages of chemical precipitation include the availability of affordable precipitants and low initial investment costs.

However, a significant disadvantage is the generation of substantial amounts of sludge, which requires additional procedures for metal extraction. The little amount of metal ions and the challenges associated with sludge disposal can experience end duringly negative consequences on ecosystem (Barakat, 2011; Fu and Wang, 2011).

3.3 Technique of Ion-exchange

The removal of various metal ions from effluent often involves the use of the ion exchange technology. This process involves replacing the ions present in the wastewater with different ions, resulting in recyclable, purified water. Different coatings of ion exchange,employed to treat the effluents contain diverse metallic ions, inorganic and natural contaminants (Bisht and Agarwal, 2017). Ion exchangers effectiveness largely depending to the kind of functional groups, may be anionic,ionic, or chelate, as well as their formation, whther they areреal or synthetic. Inorganic resins familiar to possess strong attarct ion to metallic ions and exhibit stability even at elevated temperatures (Ahmad et al., 2018). However, their chemical and mechanical strength is relatively low, and they are not naturally replenished (Pathania et al., 2017).

The advantages of ion exchange techniques are their low price, environmental safety, as well as withstand in extreme conditions (Fu and Wang, 2011). Ion exchange favored because of its excessive absorption capacity for hazardous materials, fast kinetics, ability to treat(Fu and Wang, 2011). Moreover, ion-exchange resins as it may be regenerated as well as utilize through trnsformation procedure. Ion exchange benefits involve the formation of dense matter, high processability, elevated elimination productivity, selective binding of specific resinous ligands to particular metal cations, and rapid kinetics. However, drawbacks include the need for a secondary wastewater pre-treatment system, which may not appropriate to many kinds of materials and can occur significant operating and investment expenditure. (Kurniawan et al., 2006; Fu and Wang, 2011; Dabrowski et al., 2004). Synthetic resins frequently utilized materials in ion - exchange processes and have remarkable efficiency for eliminating toxic materias through solutions. The absorption through ions of toxic materiaos, resence of ion-exchange influenced through factors like initial concentration, temperature, pH level, as well as retention duration (Kaur and Jindal, 2018).

Organic ion exchangers are created through the process of polymerization, which involves connecting organic monomers bring into existance bigger and more complex molecular structure. Efforts being made to develop ion exchangers that combine in organic and organic components for adjustment to their structural composition, enhance their totalstrength,also improve their productivity about precise ions of toxic materialas(N.K. V, A. Mohan, and J. C, 2016).

3.4 Techniques for Membrane filtration

The technique of Membrane filtration involves applying pressure to a liquid and passing it through a porous membrane or filter, thereby separating particles in the liquid (Kurniawan et al., 2006). Membrane filtration techniques may broadly be classified in three types: nanofiltration, reverse osmosis (R.O), and ultrafiltration (Barakat, 2011). Ultrafiltration, with a pore size of 5-20 nm, can effectively remove suspended solids, macromolecules, and heavy metals from inorganic solutions while retaining solutes with small molecular masses, including water (Kurniawan et al., 2006; Barakat, 2011) Nanofiltration utilizes steric (sieve) and electrical (Donnan) effects as mechanisms for separation. The establishment of a Donnan potential enables the rejection of negatively charged ions and their co-ions into waste water from the membrane of nanofiltration (Kurniawan et al., 2006). Smaller charged solutes than the pores of membrane

and discarded along side salts, as well as sizable neutral solutes with charges, contribute significantly to this process. Membranes of reverse osmosis (RO) are designed to a size of pore between 0.0005 and 0.001 microns, allowing water to pass through while trapping heavy metals inside (Kurniawan et al., 2006; Fu and Wang, 2011). By applying an elevated hydrostatic pressure in reverse osmosis, compared with osmotic pressure, effectively separating non-ionic chemicals from water (Kurniawan et al., 2006).
The advantages of membrane filtration include its small footprint, adjustable pressure, high separation capability, and selectivity, while the drawbacks include low permeate flux, exorbitant operational expenses generate by membrane deterioration,as well as significant expenditure on membrane materials (Kurniawan et al., 2006; Barakat, 2011; Malviya and Singh, 2011).Membrane filtration operation is govern byvarious constituents like temperature, surface porosity, pressure, membrane pore structure,pH,size, anti-fouling properties, and feed concentration (Saeid et al., 2016).
Reverse osmosis and ultrafiltration are considered effective membrane processes due to their low operating pressure requirements, resulting in reduced capital and operating expenses (Ahmad et al., 2020). Enhanced nanofiltration membranes using chitosan have gained recognition for their flexibility, increased permeation variability, high elimination ratios, and moderate power requirements (Moradi et al., 2020). Important investigation revealed that elimination among ions like Ni(II) ,Cu(II), Co(II), and Zn(II) using chitosan-enhanced membrane filtration, as highlighted by Juang and Shiau in 2000. By utilization of Nanofiltration hollow-fiber membrane to remove the toxic elements through real plating effluent having chromium, nickel and copper, it was noticed that the membrane rejection rates for alltoxic elementsexceeds984.8% through out the process.
Membrane filtration offers various benefits compared to conventional methods, together with enhance the separation effectiveness, reduction in energy consumption, scalability, efficient recovery of toxic metal ions, as well as environmental friendliness. It does, however, have drawbacks like poor permeate flux, expensive membrane materials as toxic elements elimination,as well as higher operational expenses due to membrane fouling.
3.5 Adsorption technique
Adsorption is the process by which material in a fluid state moves and adhere to a solid surface, called adsorbent, through physico-chemical reactions (Kurniawan et al., 2006). In general, ions of metal adsorption on a solidified sorbent involves three processes: (1) Metal ion transportation of mass mixture on the adsorptive surface.(2) absorption on an adsorbent surface. (3) carbon nanotubes (CNTs) and modified biopolymers derived from chitosan transfer within the sorbent (Bhatnagar et al., 2009).
Adsorption relies on-the physco-chemical reactionsin-between molecules as well as adsorbent's surface (Mahmoud et al., 2018; Farag et al., 2018; R. Kecili and C.M. Hussain, 2018). Chemical adsorption comprises of new links generation with in particles including adsorbent, while physical adherence is characterized through Coulomb forces and intermolecular forces (R. Kecili and C.M. Hussain, 2018). The adsorbent surfaces in this process are coated with the adsorbate, providing a large interfacial and elevated adsorptive area. Sorbents as it may be recreated through sorption, which allows the reversal of the adsorption process.
Various materials can be used to create adsorbents, including natural substances, agricultural byproducts, and industrial byproducts such as steel slag. Carbon nanotubes (CNTs), activated carbon (AC), Iron Powder as well as cost-effective adsorbents like peat, biomass, and clay, are among the most effective adsorbents in the adsorption process. This adsorption method offers significant economic and environmental advantages, such as low operational costs, wide availability, profitability, and high output. Many economical adsorbtives generated through organic materials, wastes from agriculture,as well as mechanized out put are employed to remove toxic elements from electroplating effluents, including Cr(III), Zn(II),Cr(VI), Cu(II), Ni(II), and Cd(II), (Agustiono et al., 2006).
Adsorbent effectiveness in absorbing substances depends on its porousness, surface area, adsorptive quantity, durability of water, recyclable, and productivity of hazardous material. The adsorbent material will exhibit chemical and hydrothermal stability to endure harsh eco-friendly environment(Gu et al., Manyangadze et al., 2020). The absorbing ability is affected through parameters such as adsorbent quantity, contaminants properties , climate, pH, and exposure duration (Dhoble and Ahmed 2019). However, absorption procedure drawbacks include low selectivity and recovery efficiency, as well as the generation of waste products.
3.6 Electrochemical techniques

In 1889, the electrochemical method was first utilized for sewage treatment in England. Techniques of electrochemical have been found to outperform conventional physicochemical methods for treating electroplating wastewater, as noted by Chen et al. (2009b). Treatment utilising electrochemistry serves as an environmentally friendly alternative to existing remedial techniques for refractory contaminants. Techniques like electrodeposition, electrocoagulation (EC), electrodialysis (ED), electro-flotation (EF), and electrooxidation (EO) can be readily employed to mitigate industrial effluents.

Electrochemical processes involve the use of electric current to achieve various treatment objectives. In the electroplating industry, metal ions are plated onto a cathode surface through electrodeposition, facilitated by the application of electric current (Fu and Wang, 2011). Electrocoagulation, electrodeposition, and electrodialysis are commonly employed electrochemical treatment techniques in electroplating. Electrocoagulation producestable coagulantsthrough electrolyzing ions of iron ions or aluminium, aiding toremove flocculated particles present in electroplating water (Fu and Wang, 2011; Al-Shannag et al., 2015). Despite the advantages of electro-chemical processes, such as minimal chemical requirements, good selectivity, controlled operation, and absence of sediment formation, there are There are certain disadvantages, such as a significant working capital., elevated operational costs because of power consumption and expensive power supplies (Kurniawan et al., 2006; Fu and Wang, 2011; Gunatilake, 2015).

Electrochemical processes are considered highly efficient in removing various pollutants. They offer advantages over traditional methods, such as complete mineralization, reduced or no use of synthetic indicators, prevention of the generation of new hazardous species, and lower energy requirements. However, they may entail a significant initial investment and occasional electrode fouling. Electrochemical methods performance depending upon elements namely the electrodes used, pH,applied potential, and electrolyte composition (Caizares et al., 2005). Electrochemical processes, including electrochemical oxidation processes (e.g., electro-Fenton and photoelectrocatalytic processes), are categorized under advance oxidation processes (AOPs) these methods experienced increasing attention over the last few years.

3.7 Electrocoagulation

Electrocoagulationis an electrolytic analysis method that utilizes unidirectional current charge supplied to anodeto neutralize charged species in water, such as metal ions like aluminum (Al) and iron (Fe). The method entails the in place generation of chemicals (coagulants), which help remove impurities through precipitation or flotation, thereby eliminating suspended, dissolved, and emulsified pollutants. EC is a multi-step, multi-mechanism method for removing toxic elements efficiently with other pollutants simultaneously. This procedure includes electrolytic reactions at the electrode surfaces, production of aqueous phase coagulants from anodic metal hydroxides, adsorption or encapsulation of contaminants in flakes, and their subsequent removal through sedimentation, electroflotation, or adhesion to bubbles (Prajapati et al., 2016). The coagulant responsible for the neutralization process is often produced on-site through simultaneously dissolving ions of metal from anode and producing hydroxide ions on cathode (Islam and Sustain, 2019). The cathode emits hydrogen gas which can be captured or utilized. EC is known for its simplicity, minimal chemical requirements, effectiveness, short treatment time, and low sludge production (Chen, 2004).

Over the last twenty years, electrocoagulation(EC)method widely applied to industrial effluents to remove the noxious element ions, as well asCu, Cr, Hg, Ni, Cd, Fe, and Zn, (Al-Qodah and Al-Shannag, 2017). The production of chemicals (Coagulants) through the electrolytically dissolving Aluminium (Al) either iron (Fe) ions through the respective plate in EC. The cathode's hydrogen gas aids in flocculating particles, while coagulant ions are formed at the anode (Fu and Wang, 2011; Sharma et al., 2020a). EC is faster in removing effluents from wastewater compared to chemical coagulation or adsorption on activated carbon. Studies have shown successful removal of Pb and Cu using EC with specific electrode configurations and operating conditions.

While EC offers benefits such as rapid treatment, simplicity, cost-effectiveness, and environmental friendliness, there are also drawbacks. The sacrificial anodes used in the process need to be replaced periodically due to metal deposition and passivation. The sludge generated during EC may contain significant levels of hazardous metals and requires appropriate handling to avoid environmental risks. Furthermore, the efficacy of the EC process perhaps influeced via parameters like electrode fouling as well as appearance of interfering substances (Elazzouzi et al., 2021; Zheng et al., 2017). Nonetheless, EC remains an affordable and favourable method for treating effluent and water.

3.8 Electrodeposition

The electrodeposition approach is commonly employed to recover harmful metal ions from wastewater by utilizing appropriate electrodes. The technique ensures safe restoration of toxic elements from sewage without leaving behind any lingering toxins. Positively charged metal ions decreases also stimulated on conductor through a redox reaction during the electro deposition process and on the anode negatively charged metal ions are oxidized.That leads to the minimization and electro deposition of toxic substances on cathode,while biotic pollutants into effluent are eliminated at the anode (Chang et al., 2009).

The electro deposition approach offers several advantages, including metal restoration into its refine dstructure, low operational expenses, with convenient sludge disposal.It was found that no additional reagents were required for the electro deposition of six noxious substances on reticularshiny carbon plates, and the process did not generate any sludge.Due to its selectivity, cost-effectiveness, and absence of stable tailings for metal recovery, electrodeposition is considered advantageous and reliable (Oliveira et al., 2018; Du et al., 2018).To extract Ni(II) ions through actual electroplating effluent with nickel, for further developmenta fixed-bed coating adsorption process was employed. Subsequently, the presence of concentrated Ni(II)ionsin altered suspension be converted into nickel(Ni) sheets through electrocoating.(Li et al., 2019).

3.9 Electro flotation

Electroflotation, a solid-liquid disassociation technique which utilizes water electrolysis to generate gases namely hydrogen as well as oxygen, resulting tiny lather formation that carry impurities to the water surface. This allows for easy separation of effluents as the impurities rise to the top of the liquid phase. As a result of water electrolysis, heavy metal particles adhere to or are trapped within the hydrogen and oxygen bubbles, causing the formation of flakes in the solution (Chen, 2004). The EF process involves two main phases. In the first phase, flocs are formed and flotation occurs, leading to the rise of the resulting foam. In the second phase, the settled flocs are separated and the foam is removed, filtering out the accumulated pollutants. Kolesnikov et al. (2015) investigated various chemical agents impact covering physicochemical characteristics of the dispersed form for the removal of zinc(Zn) hydroxides, nickel(Ni), and copper(Cu). Sun et al. (2019) conducted tests using iron electrodes combined with manifold paper and micro- and lab-scale ultrafiltration (UF). They found that combining non-aeration EF with microfiltration, aeration, settling, and paper filtration produced excellent results in terms of residual Ni, Fe, and turbidity removal. They concluded that using microfiltration in conjunction with an aeration-enhanced EF technique could be effective for removing Ni and Fe, potentially meeting the requirements of the metal finishing industry. This approach is particularly beneficial for regional purification systems as it minimizes the generation of secondary contamination.

Electroflotation is commonly employed to remove the toxic elements through manufacturing waste water. Heavy elements such as nickel,lead and iron,copper,zinc,may be succesfully elimate from factory wastewater utilizing EF in various applications (G.Z. Kyzas and K.A. Matis, 2016). The hybrid system, yielded significant improvements by combining ferrous clay as an adsorbtive with an aluminium plates for the electroflotation technology. The optimal outcomes showcased a remarkable decrease in the concentration of Cd(II), Pb(II), Cu(II) andNi(II), ions, with reductions of 36.71%, 21.59%, 23.43% and 50.11% successively (Teixeira et al., 2022).

3.10 Electrodialysis Process

A promising process of wastewater treatment,electrodialysis (ED) that originated from desalination research in the 1950s (Azimi et al., 2017). Ion exchange membranes allow the movement of ionized groups in an emulsion at the same time the electrodialysis (ED) process provides an electric voltage(Bruggen and Vandecasteele, 2002). Ions move in mixture via anionic and cationic exchange membranes as they traverse to cell compartment in the ED method.

The performace of ion exchanged membrane during electrolysis of Co(II) and Ni(II))ions through chemical mixture. They compared dual cat-elec exchange membranes, namely,Perfluorosulfonic acid and sulfonating polyvinylidene fluoride membrane, under identical working atmosphere. The Nafion 117, perfluorosulfonic acid membrane exhibited eliminating efficiencies 69% Ni(II) with Co(II)90% at primary elememt concentrations of 0.84x 10-3 and 11.72x10-3 g/L, successively.

An electrodialysis (ED) model apparatus with novel ion exchange membranes since the rejection of chromium(VI) ions. Electrodialysis (ED) units effectiveness assessed under different applied potentials, pH values, preliminary chromium (Cr) concentrations, and volume velocities. Promising results were achieved, with the highest impurity limitation for Cr set at 0.1 mg/L, even at lower starting concentrations below 10 ppm. Many researchers focus on electrodialysis utilizing ion exchange membranes for the removal of chromium (VI), and chromium (III)ions, with detachable cells using ion exchange membranes facilitating the elimination process (Mirium et al., 2005).

The electrodialysis machine for electrolysis consists of a water-based, single-stage electro-electrodialysis setup with a purification device that removes metallic contaminants and recovers chromic acid. To treat the effluent discharge through electroplating manufacturing,a two-stage electrodialysis system for chromate retrieval and an experimental setupwas established to remove chromium (VI) from potable water (Frenzel et al., 2005).

Nataraj et al. (2007) and Ma et al. (2014), studied that chromate ions in various quantities can be effectively removed from chrome plating wash discharge utilizing deionization and electrodialysis. ED offers several advantages, such as generating a stream with high concentration to retriev as well as removing unwanted waste water through discharge.It couid also employed to remediate effluent that contain essential elements like Cu and Cr. Since ED is a membrane process, precautions must be taken to avoid stack damage by ensuring watch ful functioning, cleaned fodder, and systematic maintenance (Barakat, 2011).

A cost-effective approach was adopted to recover nickel through real plating effluent by combining electrocoating with an absorption preliminary treatment technology. The findings demonstrated that the adsorption pretreatment effectively simplified the composition of the wastewater, eliminating 85% constituents oftotal organic carbon (TOC). Moreover, pretreatedeffluen utilized for electrodeposition, leading to a notable reduction in inefficient energy consumption by 50% (Li et al., 2023).

3.11 Electrooxidation

Electrooxidation (EO) has been extensively researched as a wastewater treatment method, with its initial application in the electrochemical breakdown of cyanide in the late 1900s (Kuhn, 1971). Redox reactions occur at the anode (oxidization of contaminants) as well as cathode (toxic elements reduction) during electrochemical process. The proceedure has been long been employed as a technique for removing of toxic element. Electrochemical advanced oxidation (E-AOP) procedure have gained more attention for the application and study of electrochemical oxidation processes aimed at mineralizing biotic particles within industrial effluent (Muddemann et al., 2019). Electrolytic pre-oxidation is commonly used in these methods, and several patents exist for their implementation. Electrochemically formulated oxidising agents may be produced directly or indirectly by successive inert species reactants (Botte, 2017). Direct electrolysis or anodic oxidation takes place at the anode (M), where organic pollutants in water directly undergo electro-oxidation or electrolysis using an electron acceptor. In this process, the use of peroxynitrite, thatoxidizes specific natural pollutants as a possibility below the potential oxygen evolution reaction (OER), is commonly employed.

Though, electrode fouling and the development of polymer coatings at electrode surface can limit the efficiency of direct oxidation. Indirect oxidation strategies offer advantages over direct oxidation by utilizing the transformation of the oxygen zone without generating waste or requiring oxidation catalysts in the solution. Direct electro-oxidation of pollutants on the anode may take place by chemosorption or physical adsorption of active oxygen species. The EO technique is extreamely successful in removing natural as well as inorganic pollutants while being environmentally safe.

Even at high concentrations (e.g., 50g/L CN). EO technique utilizes successfully to remove the cyanide (CN) from effluent, Meanwhile electro oxidation(EO), metal ions could be accumulated on conductor,at the same time ions of cyanide be eradicated on electrode (Cheng et al., 2002). Valinien et al. (2015) investigated the electro oxidation(EO) procedure for ions of cyanide(CN)remove from effluent using a low-cost anode consisting of a Pt-covered Ti electrode with an average thickness of 600 nm. In their study, an electro oxidation (EO) of extreamely concentrated cyanide(CN) mixture (0.1 M KCN or 2600 mg/L) was achieved at a consistent voltage with an amount of charge0.025ampere/cm^2. At a current efficiency of 60% and a charge transfer of 69 kC/L, ions of cyanide(CN) were almost removed, minimising the concentration from 3.55g/l to 0.00568 g/l. simultaneously removed CN and Cu using stainless steel electrodes in an EO process. The direct electro-oxidation process was setup to be successful and economical at pH 13, with a copper recovery with the appearance of refined metal electrod deposited on the cathode (Kazeminezhad and Mosivand, 2017). They achieved a reduction of Cu concentration by 79% (from 470 mg/L) in one and half hour with a power usage of 17000watts/q, resulting in the deposition of 0.3353 g of Cu at cathode. Additional research by Kazeminezhad and Mosivand (2017), Ni and Cu were extracted from wastewater using sacrificial iron (Fe) sheets in an electrolytic cell.

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 22s, 2025
https://theaspd.com/index.php

3.12 Advanced oxidation processes (AOPs)

In effluent analysis, (AOPs) are crucial, to further remove contaminants through reactions with hydroxyl radicals. AOPs assist limited decomposition of imperishable organic matter, transforming, although they are more expensive and often used as a pretreatment step before traditional methods (A.C. Vincenzo Naddeo, 2013). These processes chemically modify pollutants and aim for complete mineralization, aiding to remve the pollutantswhich resist being treated biologically(Y. Deng and R. Zhao, 2015). AOPs are particularly effective in reducing the levels of contaminants to improve the organoleptic qualities of water, decrease the concentration of chemicals produced during pre-treatment processes, and eliminate the adverse health effects of disinfectants and oxidants. AOPs may be broadly categorised into two categories (Heberling et al., 2018):

Alternatives to photochemistry: Fenton systems, ozone, peroxone, ferrate, and catalytic ozone are included in this group

Techniques employed in Photochemical: These techniques include photocatalytic ozonation, ozone-UV radiation, ultrasound/sonication, , (UV/titanium dioxide), photo Fenton/Fenton-like systems,ultraviolet radiation, electron beam irradiation, as well as ozone-UV radiation. AOPs have been increasingly employed recently for the treatment of manufacturing effluents (Korpe et al., 2019). This effective analysis method utilizes hydroxyl radicals to effectively remove persistent contaminants. The fundamental principle behind AOPs is the production of radicals with hydroxyl through oxidants, photocatalytic ozone, or oxidants in combination with ultraviolet light. In certain instances the combinations of two or more radical agents are possible. Hydroxyl agents primarily target already formed organic complexes, and the attack of hydroxyl radicals completely destroys organic compounds, reducing the contaminant content from several hundred ppm to under 5 ppb.

Theoretically, AOPs aim to completely mineralize organic molecules into CO_2 and H_2O. Photocatalytic AOP and the best common techniques for treating water are electro-Fenton. These AOPs effectively degrade metal-polluted effluents while maintaining high treatment efficiency. By producing highly reactive oxidizing agents like hydroxyl radicals (OH), AOPs can thoroughly decompose organic contaminants into harmless byproducts such as inorganic salts, CO_2, and water.

However, like various analyses methods, advanced oxygen processes (AOPs) carry several drawbacks along side their higher cost correlated with biological approaches. As an example, the consequence of advanced oxygen processes(AOPs) responce themselves can be hazardous substances that need to be carefully analyzed. Therefore, the use of AOPs requires resource consumption and may have limited downstream operational efficiency.

3.12 Photochemical advanced oxidation process

Photocatalysis emerges as promising form of photochemical advanced oxidation process for wastewater treatment due to its easy implementation, cost-effectiveness, elevated rate of degradation, monimal harmful,with excellent durability. The concept of photocatalysis involves the use of semiconductor catalyst particles, typically titanium dioxide (TiO_2), in combination with low-energy UV light reducesions of metal present in an electrolysis (Chen D. and Ray A. K., 2001). A well-established research area in wastewater treatment and environmental protection is semiconductor photocatalysis, particularly employingultra violet illuminated TiO_2 in order to detoxify harmful chemicals in liquefied mixture (Meichtry et al., 2007). Catalyses process of TiO_2 is attributed to its electronic structure and photoelectric properties. The photocatalytic reaction can be explained in terms of band theory, where $_{TiO2}$ possesses valence and conduction bandswith anenergy band gapof 3.20 electronic volt(eV). Other semiconductor photocatalysts, such as TiO_2 (Tryba et al. 2019), zinc oxide (Shen et al. 2008) also CdS have also been studied for their photocatalytic properties. However, TiO_2 is often preferred over other semiconductor photocatalysts due to its advantageous attributes such as being non-toxic, chemically stable, affordable, and highly efficient for applications in air decontamination, water purification, contaminant adsorption, and wastewater treatment.

Photocatalysis allows for the simultaneous destruction of both inorganic as well as natural pollutants, including toxicions material, cyanide (CN-), along with nitrite (NO_{2-}) compounds. Photocatalytic oxidation and reduction be commonly employed processes to remove the pollutants. Current research field focuses on the photocatalytic rectification of ions of metal in wastewater, particularly lead (Pb), mercury (Hg), and chromium (Cr) (Luo et al., 2017). Inelectroplating industry, which is a major producer of highly hazardous cyanide, TiO_2-based photocatalysis can transform harmful cyanide species into innocuous forms such as N_2, CO_2, or CO_3^{2-}.

Studies have also explored the modification of TiO2 photocatalysts to enhance their performance. For example, the incorporation of neodymium (Nd) into TiO2 through a sol-gel process has been found to enhance photocatalytic chromium receiving ultra violet irradiation. On the TiO_2 surface, Nd ions act as electron assemblage locations, improving the dissociation of electron-hole pairs and promoting reactions of photocatalytic reduction. Additionally, anodized immobilization processes have been created to get around the restrictions of TiO_2 dust, allowing efficient photocatalytic reduction of hexavalent chromium to unhazardous chromium (III) receiving ultra violet illumination. In photocatalysis,electron-hole pairs are produced in catalyst molecules when semiconductor particles are exposed to UV light carrying energy surpassing the photocatalyst's band gap (Chen D. and Ray A. K., 2001).

The electrons produced can then participate in cathodic processes by reacting with scavengers. TiO_2, ZnO, CeO2, CdS, and ZnS are commonly used semiconductor photocatalysts derived from chalcogenide compounds. The metals can be deposited on photocatalyst's surface and later on separate from slurry mechanically or chemically. The photocatalytic process offers the advantages of simultaneous metal recovery and organic contaminant removal, along with the production of less toxic byproducts. However, photocatalysts have some drawbacks, including high capital costs, long lifetimes, and limited applications (Barakat M. A., 2011; Chen D. and Ray A. K., 2001).

A nano catalyst aminopropyl triethoxysilane nano-particles was prepared using a straightforward co-precipitation method to treat electroplating wastewater under visible light. Remarkably, under optimal conditions, after 1440 minutes of treatment, arround 82.96% hexavalent chromium present in a genuine water sample had been eliminated.

3.13 Process of Electro-Fenton

A useful and a powerful technique is the Electro-Fenton procedure which reduces various types of harmful contaminants in wastewater. It is a variation of the Fenton process that utilizes less energy to treat wastewater compared to the original Fenton process. Electro- Fenton technique discovered by Fenton in 1890s, which generate highly reactive hydroxyl radicals (OH•) as a result of ferrous ions reacting (Fe2+) as hydrogen peroxide (H_2O_2). An iron-based catalyst, often in the form of Fe2+, and an oxidizing agent, typically H_2O_2, are utilizes in the process of Electro-Fenton.Fentonprocess comprises to two categories:

i) homogeneous and

ii) heterogeneous.

When using homogeneous Fenton process, $H_2O_2$with Fe2+ combine to produce extremelyreactive OH• radicals. These radicals then inter act with dissolved pathogens, organic compounds,colloidal suspension and bacteriacompletely degrading them in water withcarbon dioxide (CO_2). Procedureof dissolving toxic ions using Fenton oxidation illustretad. Studies have shown high efficiency in degrading heavy metals such as Ni^{2+} and NIEDTA using homogeneous Fenton oxidation (Asgari et al., 2016; Wang et al., 2019). Wastewater analyses byelectro-fenton procedure has several advantages, including ease of handling, relatively inexpensive chemicals, and no energy consumption. However, it has some drawbacks, such as the requirement for strict pH control (Wang et al., 2016). Throughout the heterogeneous Fenton procedure, solid catalysts used to enable the reduction of soluble metal ions over a wide pH range, similar to the oxidation process in Fenton. A Fenton-like catalystefficiently utilizesto remove the heavy material compounds, such as polymer-based nanoscale hybrid Fe(III) oxide heptafluoro dimethyl octanedione (HFOD) catalyst. The heterogeneous Fenton approach offers benifitslikepotential to limit the sludge rate formation by adjusting the reaction time and slight leaching of metal ions from the catalyst.

When a redox pair is added to the solution, H_2O_2 decomposes into highly reactive OH• radicals. The Fe^{2+}/Fe^{3+} pair yields finest results in Electro-Fenton process. Fe^{2+} can be regenerated through chemical or electrochemical methods, allowing the process to be repeated.

Overall, Electro-Fentonprovidemany unique benifits, including improved eliminatng efefctineness, easy todesign reacter, enhancement of natural degradation in the effluent, continuous H_2O_2 production through O_2 depletion or Fe^{2+} regeneration at the iron anode, lower treatment costs, minimal secondary contamination, and the ability to maintain the electriccurrent andpotential -difference during procedure of electrolysis (Xu et al., 2021). The process is effective in acidic environments, but its applicability is primarily limited by the need for iron (Fe) elimination (Burgos-Castillo et al., 2018; An et al., 2019). In electro-Fenton procedurePyridine-N doping has been used to modify carbon-felt cathodes(Zhou et al., 2020).

4. Post Treatment and Sludge Handling:

Following the treatment processes, the post-treatment stage plays a pivotal role in ensuring compliance with regulatory discharge standards and in maintaining system sustainability. The effluent exiting the EC unit contains flocs, fine particles, and residual contaminants that are further refined through the integrated membrane (IM) system comprising microfiltration (MF), nanofiltration (NF), and reverse osmosis (RO) membranes. These successive membrane stages progressively eliminate suspended solids, dissolved salts, heavy metals, and organic contaminants, achieving overall removal efficiencies exceeding 99% for heavy metals and over 97% for other pollutants such as COD, TN, TP, and petroleum hydrocarbons.

In tandem with water purification, sludge generation is an unavoidable outcome of the EC process. Flocs formed during EC—composed primarily of metal hydroxides, adsorbed pollutants, and precipitated solids—settle within the reaction chamber. Effective sludge management is critical to the sustainability of the treatment system. Sludge is periodically discharged through a bottom valve at hourly intervals during operation to prevent accumulation and interference with the EC process efficiency. The sludge exhibits relatively low volume compared to conventional chemical coagulation due to the inherent efficiency of EC in floc formation with minimal chemical input. Post-treatment sludge handling involves dewatering and, where feasible, metal recovery. As electrochemical methods offer high selectivity and minimal chemical addition, the resulting sludge is often amenable to further processing, including potential metal extraction or safe stabilization for disposal. Additionally, membrane maintenance is addressed through a regeneration cycle, wherein membrane flux recovery consistently exceeded 94%, indicating robust performance and cost-effectiveness of the cleaning protocol.

Future improvements in sludge handling may include integration with advanced dewatering units and resource recovery technologies to enhance economic and environmental viability. Overall, the combined EC–IM system not only ensures effective wastewater treatment but also provides a manageable pathway for sludge disposal and resource recovery, making it a comprehensive solution for electroplating wastewater remediation.

5. Discharge or Reuse (Zero Liquid Discharge, Water Recycling, etc.)

The ultimate objective of advanced electroplating wastewater treatment systems is to meet stringent discharge regulations or enable water reuse, thereby advancing toward zero liquid discharge (ZLD). In the current study, the integration of electrocoagulation (EC) with a multistage membrane filtration system comprising microfiltration (MF), nanofiltration (NF), and reverse osmosis (RO) ensured that treated effluent met or surpassed the discharge standards stipulated in GB 21900-2008 for electroplating pollutants. The multi-barrier membrane process facilitated the progressive elimination of suspended solids, multivalent ions, and dissolved organics. The MF stage primarily targeted particulate matter and floc residues, while NF and RO stages were instrumental in rejecting divalent and monovalent ions, respectively. Final effluent characteristics, including heavy metals such as Zn^{2+}, Cu^{2+}, Ni^{2+}, and Cr (as TCr), were reduced to below permissible limits, with removal efficiencies exceeding 99% under optimal operating conditions. In parallel, organics (measured as COD), total nitrogen, phosphorus, and hydrocarbons were removed with efficiencies above 97%, rendering the water fit for reuse. The high-quality permeate obtained from the RO stage presents viable opportunities for internal recycling within industrial operations, such as rinsing, plating bath replenishment, or cooling water makeup. The concentrated retentates from each membrane stage are systematically collected and recirculated or sent to evaporation units, supporting a ZLD configuration. Additionally, the modular nature of the IM system allows for continuous monitoring and optimization, ensuring sustained performance and compliance with both discharge and reuse criteria.

Implementing ZLD not only aligns with environmental regulations but also minimizes freshwater consumption and reduces the environmental footprint of electroplating facilities. Furthermore, by concentrating waste streams for potential metal recovery, the system promotes circular economy principles, turning waste into resource streams. Overall, the proposed EC–IM process demonstrates the potential for closed-loop water management and sustainable industrial wastewater treatment, facilitating either safe discharge or complete reuse in alignment with emerging water conservation strategies.

CONCLUSION:

Electroplating industries, while essential to modern manufacturing, pose significant environmental challenges due to the discharge of toxic heavy metals and chemical pollutants. Addressing these issues requires a comprehensive and sustainable approach to wastewater treatment. A range of treatment techniques physical, chemical, adsorption-based, and electrochemical offer pathways for effective remediation. Among these, electrochemical methods hold significant promise due to their high efficiency, adaptability, and compatibility with sustainability goals.

The integration of Zero Liquid Discharge (ZLD), water reuse practices, and advanced sludge handling can drastically reduce the environmental footprint of electroplating operations. Moreover, aligning these technologies with the Sustainable Development Goals (SDGs) particularly those related to clean water (Goal 6), responsible consumption (Goal 12), climate action (Goal 13), and life below water and on land (Goals 14 and 15) is crucial for long-term environmental stewardship. Moving forward, cross-disciplinary collaboration, governmental support, and industry commitment are essential to foster innovation, ensure regulatory compliance, and promote cleaner production strategies. With continued research and practical implementation, the electroplating sector can transform from a major pollutant source into a model for sustainable industrial development.

Future Prospective

The future of electroplating wastewater treatment is expected to be shaped by technological innovation, environmental policies, and evolving industrial needs. Several emerging trends will likely redefine the sector:

1. Green and Sustainable Processes: Increasing global emphasis on sustainability is accelerating the adoption of eco-friendly electroplating processes. Research is directed toward reducing hazardous chemical use, minimizing waste generation, and improving energy efficiency.
2. Alternative Materials: As precious metals become more expensive and scarce, alternatives such as nanomaterials, composite coatings, and eco-safe alloys are gaining attention.
3. Advanced Coatings: The need for superior functional coatings—such as corrosion-resistant, antibacterial, or self-cleaning layers—has prompted innovation in nano and multilayer coatings.
4. Digitalization and Automation: The integration of machine learning, robotics, and advanced sensors is revolutionizing process control, quality assurance, and resource optimization in electroplating operations.
5. Microplating and Miniaturization: With growing demands in sectors like electronics and healthcare, micro- and nano-scale plating will become increasingly important for producing high-precision coatings.
6. Pilot-Scale Validation: Emphasis is needed on real-world validation of lab-scale technologies. Pilot studies using actual industrial effluents are critical to ensure scalability, reliability, and regulatory compliance.

Author Contributions: Conceptualization, methodology, formal analysis, writing—original draft preparation by Waseem Ullah Khan, data curation, writing—review and editing, by Aftab Alam, visualization & supervision, by Sirajuddin Ahmed. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

REFERENCES:

1. Achak, M., Elayadi, F., & Boumya, W. (2019). Chemical coagulation/flocculation processes for removal of phenolic compounds from olive mill wastewater: a comprehensive review. Am. J. Appl. Sci, 16(3), 59-91. [doi.org/10.3844/ajassp.2019.59.91]

2. Ahmad, A., Ahmad, H., Lokhat, D., Golandaj, A., Ramjugernath, D., & Mohd-Setapar, S. H. (2018). Recent advances in polyaniline-based nanocomposites as potential adsorbents for trace metal ions. Polymer-based Nanocomposites for Energy and Environmental Applications, 597-615.

3. Ahmad, T., Guria, C., & Mandal, A. (2020). A review of oily wastewater treatment using ultrafiltration membrane: A parametric study to enhance the membrane performance. Journal of Water Process Engineering, 36, 101289.

4. Alothman, Z. A., Naushad, M., & Ali, R. (2013). Kinetic, equilibrium isotherm and thermodynamic studies of Cr (VI) adsorption onto low-cost adsorbent developed from peanut shell activated with phosphoric acid. Environmental Science and Pollution Research, 20, 3351-3365.

5. Al-Qodah, Z., & Al-Shannag, M. (2017). Heavy metal ions removal from wastewater using electrocoagulation processes: a comprehensive review. Separation Science and Technology, 52(17), 2649-2676.
6. Al-Shannag, M., Al-Qodah, Z., Bani-Melhem, K., Qtaishat, M. R., & Alkasrawi, M. (2015). Heavy metal ions removal from metal plating wastewater using electrocoagulation: Kinetic study and process performance. Chemical Engineering Journal, 260, 749-756.
7. Alsubih, M., El Morabet, R., Khan, R. A., Khan, N. A., ul Haq Khan, M., Ahmed, S., ... & Changani, F. (2021). Occurrence and health risk assessment of arsenic and heavy metals in groundwater of three industrial areas in Delhi, India. Environmental Science and Pollution Research, 28, 63017-63031.
8. Ang, W. L., & Mohammad, A. W. (2020). State of the art and sustainability of natural coagulants in water and wastewater treatment. Journal of Cleaner production, 262, 121267.
9. Asgari, G., Feradmal, J., Poormohammadi, A., Sadrnourmohamadi, M., & Akbari, S. (2016). Taguchi optimization for the removal of high concentrations of phenol from saline wastewater using electro-Fenton process. Desalination and Water Treatment, 57(56), 27331-27338.
10. Babu, B. R., Bhanu, S. U., & Meera, K. S. (2009). Waste minimization in electroplating industries: a review. Journal of Environmental Science and Health Part C, 27(3), 155-177.
11. Barakat, M. A. (2011). New trends in removing heavy metals from industrial wastewater. Arab J Chem 4 (4): 361–377.
12. Barbosa, A. D., da Silva, L. F., de Paula, H. M., Romualdo, L. L., Sadoyama, G., & Andrade, L. S. (2018). Combined use of coagulation (M. oleifera) and electrochemical techniques in the treatment of industrial paint wastewater for reuse and/or disposal. Water Research, 145, 153-161.
13. Barry, D. M., & Kanematsu, H. (2016). Corrosion and surface finishing. Corrosion Control and Surface Finishing: Environmentally Friendly Approaches, 57-65.
14. Bazrafshan, E., Mohammadi, L., Ansari-Moghaddam, A., & Mahvi, A. H. (2015). Heavy metals removal from aqueous environments by electrocoagulation process–a systematic review. Journal of environmental health science and engineering, 13, 1-16.
15. Bhatnagar, A., & Sillanpää, M. (2009). Applications of chitin-and chitosan-derivatives for the detoxification of water and wastewater—a short review. Advances in colloid and Interface science, 152(1-2), 26-38.
16. Bilal, M., Shah, J. A., Ashfaq, T., Gardazi, S. M. H., Tahir, A. A., Pervez, A., ... & Mahmood, Q. (2013). Waste biomass adsorbents for copper removal from industrial wastewater—a review. Journal of hazardous materials, 263, 322-333.
17. Botte, G. G. (2017). Electrochemical technologies for water treatment, management, and efficiency. The Electrochemical Society Interface, 26(2), 53.
18. Burgos-Castillo, R., Sillanpää, M., Brillas, E., & Sirés, I. (2018). Removal of metals and phosphorus recovery from urban anaerobically digested sludge by electro-Fenton treatment. Science of the total environment, 644, 173-182.
19. Central Pollution Control Board (CPCB). (2006) Pollution Control Acts, Rules and Notification There Under. Delhi: Central Pollution Control Board.
20. Chang, J. H., Ellis, A. V., Yan, C. T., & Tung, C. H. (2009). The electrochemical phenomena and kinetics of EDTA–copper wastewater reclamation by electrodeposition and ultrasound. Separation and Purification Technology, 68(2), 216-221.
21. Chang, Q., & Wang, G. (2007). Study on the macromolecular coagulant PEX which traps heavy metals. Chemical engineering science, 62(17), 4636-4643.
22. Chen, D., & Ray, A. K. (2001). Removal of toxic metal ions from wastewater by semiconductor photocatalysis. Chemical Engineering Science, 56(4), 1561-1570.
23. Chen, G. (2004). Electrochemical technologies in wastewater treatment. Separation and purification Technology, 38(1), 11-41.
24. Chen, Q., Luo, Z., Hills, C., Xue, G., & Tyrer, M. (2009). Precipitation of heavy metals from wastewater using simulated flue gas: sequent additions of fly ash, lime and carbon dioxide. Water research, 43(10), 2605-2614.
25. Chen, X., Huang, G., & Wang, J. (2013). Electrochemical reduction/oxidation in the treatment of heavy metal wastewater. Journal of Metallurgical Engineering (ME) Volume, 2(4).
26. Cheng, S. C., Gattrell, M., Guena, T., & MacDougall, B. (2002). The electrochemical oxidation of alkaline copper cyanide solutions. Electrochimica acta, 47(20), 3245-3256.
27. Chongwu Guo FL (2020) Method for integrated treatment of electroplating wastewater. US Pat 20200048125A1
28. Dehghani, M. H., Nikfar, E., Zarei, A., & Esfahani, N. M. (2017). The effects of US/H2O2 processes on bisphenol-A toxicity in aqueous solutions using Daphnia magna. Desalination and Water Treatment, 68, 183-189.
29. Deng, Y., & Zhao, R. (2015). Advanced oxidation processes (AOPs) in wastewater treatment. Curr Pollut Reports 1: 167–176.
30. Dhoble, Y. N., & Ahmed, S. (2019). Treatment of wastewater generated from coke oven by adsorption on steelmaking slag and its effect on cementitious properties. Current Science, 116(8), 1346-1355.
31. Elazzouzi, M., Haboubi, K., Elyoubi, M. S., & El Kasmi, A. (2021). Development of a novel electrocoagulation anode for real urban wastewater treatment: Experimental and modeling study to optimize operative conditions. Arabian Journal of Chemistry, 14(1), 102912.
32. Farag, R. S., Elshfai, M. M., Mahmoud, A. S., Mostafa, M. K., & Peters, R. W. (2018). Green synthesis of nano iron carbide: preparation, characterization and application for aqueous phosphate removal. Environmental Division, 307-317.
33. Gao, Y., Liang, D., Zhang, Y., Chen, Y., Zhu, S., Zhang, H., & Sun, T. (2023). Using waste to treat waste: clean production of erdite/zeolite composite flocculant from groundwater treatment sludge for real electroplating wastewater treatment. Clean Technologies and Environmental Policy, 25(3), 979-995.
34. Gayathri, R., Gopinath, K. P., & Kumar, P. S. (2021). Adsorptive separation of toxic metals from aquatic environment using agro waste biochar: Application in electroplating industrial wastewater. Chemosphere, 262, 128031.
35. Guan, Z., Guo, Y., Li, S., Feng, S., Deng, Y., Ou, X., ... & Liang, J. (2020). Decomplexation of heterogeneous catalytic ozonation assisted with heavy metal chelation for advanced treatment of coordination complexes of Ni. Science of the Total Environment, 732, 139223.

36. Islam, S. D. U. (2019). Electrocoagulation (EC) technology for wastewater treatment and pollutants removal. Sustainable Water Resources Management, 5(1), 359-380.
37. Juang, R. S., & Shiau, R. C. (2000). Metal removal from aqueous solutions using chitosan-enhanced membrane filtration. Journal of membrane science, 165(2), 159-167.
38. Kaur, K., & Jindal, R. (2018). Synergistic effect of organic-inorganic hybrid nanocomposite ion exchanger on photocatalytic degradation of Rhodamine-B dye and heavy metal ion removal from industrial effluents. Journal of environmental chemical engineering, 6(6), 7091-7101.
39. Kazeminezhad, I., & Mosivand, S. (2017). Elimination of copper and nickel from wastewater by electrooxidation method. Journal of Magnetism and Magnetic Materials, 422, 84-92.
40. Kecili, R., & Hussain, C. M. (2018). Mechanism of adsorption on nanomaterials. In Nanomaterials in chromatography (pp. 89-115). Elsevier.
41. Khan, N. A., Khan, S. U., Ahmed, S., Farooqi, I. H., Dhingra, A., Hussain, A., & Changani, F. (2019). Applications of nanotechnology in water and wastewater treatment: A review. Asian Journal of Water, Environment and Pollution, 16(4), 81-86.
42. Kolesnikov, A. V., Kuznetsov, V. V., Kolesnikov, V. A., & Kapustin, Y. I. (2015). The role of surfactants in the electroflotation extraction of copper, nickel, and zinc hydroxides and phosphates. Theoretical Foundations of Chemical Engineering, 49(1), 1-9.
43. Korpe, S., Bethi, B., Sonawane, S. H., & Jayakumar, K. V. (2019). Tannery wastewater treatment by cavitation combined with advanced oxidation process (AOP). Ultrasonics Sonochemistry, 59, 104723.
44. Kurniawan, T. A., Chan, G. Y., Lo, W. H., & Babel, S. (2006). A Review Science Total Environment. Comparison of Low-Cost Adsorbents for Treating Wastewater with Heavy Metals, 366, 409-426.
45. Kurniawan, T. A., Chan, G. Y., Lo, W. H., & Babel, S. (2006). Physico–chemical treatment techniques for wastewater laden with heavy metals. Chemical engineering journal, 118(1-2), 83-98.
46. Kyzas, G. Z., & Matis, K. A. (2016). Electroflotation process: A review. Journal of Molecular Liquids, 220, 657-664.
47. L. Wang, Q. Yang, D. Wang, X. Li, G. Zeng, Z. Li, Y. Deng, J. Liu, K. Yi, Advanced landfill leachate treatment using iron-carbon microelectrolysis- Fenton process: process optimization and column experiments, J. Hazard. Mater. 318 (2016) 460–467.
48. Lanka, S., & Murari, S. G. (2022). Aquatic Plants in Phytoextraction of Hexavalent Chromium and Other Metals from Electroplating Effluents. In Advances in Bioremediation and Phytoremediation for Sustainable Soil Management: Principles, Monitoring and Remediation (pp. 129-139). Cham: Springer International Publishing.
49. Li, S., Dai, M., Ali, I., Bian, H., & Peng, C. (2023). Recovery of nickel from actual electroplating wastewater by integrated electrodeposition with adsorption pretreatment technique. Process Safety
50. Li, T., Xiao, K., Yang, B., Peng, G., Liu, F., Tao, L., ... & Deng, S. (2019). Recovery of Ni (II) from real electroplating wastewater using fixed-bed resin adsorption and subsequent electrodeposition. Frontiers of Environmental Science & Engineering, 13, 1-12.
51. Liu, C., Zhao, C., & Xu, Q. (2012). Integration of electroplating process design and operation for simultaneous productivity maximization, energy saving, and freshwater minimization. Chemical engineering science, 68(1), 202-214.
52. Lu BJ, Wu K (2020) Electroplating wastewater treatment method and development trend analysis. Mater Sci Eng 774. https://doi.org/ 10.1088/1757-899X/774/1/012092
53. Lu, B. J., & Wu, K. (2020, March). Electroplating wastewater treatment method and development trend analysis. In IOP Conference Series: Materials Science and Engineering (Vol. 774, No. 1, p. 012092). IOP Publishing.
54. Manyangadze, M., Chikuruwo, N. H. M., Chakra, C. S., Narsaiah, T. B., Radhakumari, M., & Danha, G. (2020). Enhancing adsorption capacity of nano-adsorbents via surface modification: A review. South
55. Moradi, G., Zinadini, S., Rajabi, L., & Derakhshan, A. A. (2020). Removal of heavy metal ions using a new high performance nanofiltration membrane modified with curcumin boehmite nanoparticles. Chemical Engineering Journal, 390, 124546.
56. Moreira, F. L., Costa, J. M., & de Almeida Neto, A. F. (2020). Anticorrosive Zn–Ni alloys: An alternative for the treatment of electroplating industry wastewater. Sustainable chemistry and pharmacy, 16, 100263.
57. Muraliraja, R., Selvan, R. A. S., Selvakumar, A., Franco, M., Tamilarasan, T. R., Sanjith, U., ... & Sudagar, J. (2023). A REVIEW OF ELECTROLESS COATINGS ON NON-METALS: BATH CONDITIONS, PROPERTIES AND APPLICATIONS. Journal of Alloys and Compounds, 170723.
58. Nugroho, A. P., Butar, E. S. B., Priantoro, E. A., Sriwuryandari, L., Pratiwi, Z. B., & Sembiring, T. (2021). Phytoremediation of electroplating wastewater by vetiver grass (Chrysopogon zizanoides L.). Scientific reports, 11(1), 14482.
59. Pathania, D., Thakur, M., & Mishra, A. K. (2017). Alginate-Zr (IV) phosphate nanocomposite ion exchanger: Binary separation of heavy metals, photocatalysis and antimicrobial activity. Journal of Alloys and Compounds, 701, 153-162.
60. Raju, M. V., Rao, L. N., Mariadas, K., Kumar, M. S. J., & Babu, S. R. (2019). A study on metals recovery from the waste water effluents in electroplating industry. International Journal of Civil Engineering and Technology, 10(02), 1033-1040.
61. Schalk, N., Tkadletz, M., & Mitterer, C. (2022). Hard coatings for cutting applications: Physical vs. chemical vapor deposition and future challenges for the coatings community. Surface and Coatings Technology, 429, 127949.
62. Sharma, D., Chaudhari, P. K., Dubey, S., & Prajapati, A. K. (2020). Electrocoagulation treatment of electroplating wastewater: a review. Journal of Environmental Engineering, 146(10), 03120009.
63. Sun, J., Li, M., Zhang, Z., & Guo, J. (2019). Unravelling the adsorption disparity mechanism of heavy-metal ions on the biomass-derived hierarchically porous carbon. Applied Surface Science, 471, 615-620.
64. Teh, C. Y., Budiman, P. M., Shak, K. P. Y., & Wu, T. Y. (2016). Recent advancement of coagulation–flocculation and its application in wastewater treatment. Industrial & Engineering Chemistry
65. Tryba, B., Jafari, S., Sillanpää, M., Nitta, A., Ohtani, B., & Morawski, A. W. (2019). Influence of TiO2 structure on its photocatalytic activity towards acetaldehyde decomposition. Applied Surface Science, 470, 376-385.
66. Wang, L., Yang, Q., Wang, D., Li, X., Zeng, G., Li, Z., ... & Yi, K. (2016). Advanced landfill leachate treatment using iron-carbon microelectrolysis-Fenton process: process optimization and column experiments. Journal of hazardous materials, 318, 460-467.
67. Xu, T., Zheng, X., Zhou, Y., Zhu, C., Hu, B., Lei, X., ... & Yu, G. (2021). Study on the treatment of Cu2+-organic compound wastewater by electro-Fenton coupled pulsed AC coagulation. Chemosphere, 280, 130679.

68. Yadav, M., Singh, G., & Jadeja, R. N. (2021). Physical and chemical methods for heavy metal removal. Pollutants and Water Management: Resources, Strategies and Scarcity, 377-397.
69. Zheng, T., Wang, J., Wang, Q., Meng, H., & Wang, L. (2017). Research trends in electrochemical technology for water and wastewater treatment. Applied Water Science, 7, 13-30.
70. Zhou, H., Luo, J., & Chen, Y. (2020). Nitrogen moieties-dominated Co–N-doped nanoparticle-modified cathodes in heterogeneous-electro-Fenton-like system for catalytic decontamination of EDTA-Ni (II). Chemosphere, 239, 124743.