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Review Article

Challenges in using Electrocoagulation Process in Removal of Nickel Metal in Wastewater: a Literature Review

Muhammad Ghozali Harahap[1*], Muhammad Sonny Abfertiawan[2], Mindriany Syafila[2]
[1]Department of Environmental Engineering, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Bandung, Indonesia
[2] Water and Wastewater Engineering Expertise Group, Institut Teknologi Bandung, Indonesia
*Corresponding Author, email: ghozaliharahap21@gmail.com

Abstract
In recent years, the surge in nickel production, driven by the growing demand for electric vehicle batteries, has raised concerns regarding environmental consequences. The nickel mining and processing industries contribute to increased nickel levels in wastewater, presenting a serious threat to aquatic ecosystems and human health. This article emphasizes the urgency of developing effective technologies for treating nickel-contaminated wastewater. Electrocoagulation emerges as a promising method, providing high efficiency, minimal sludge production, and cost-effectiveness. The article critically and systematically reviews the potential of the electrocoagulation process in nickel removal from wastewater. In the review, we identify and analyze nearly 32 studies published from 2013 to 2023. We discuss contaminant removal mechanisms and analyze trends in the use of operational parameters. This article identifies the most commonly applied conditions: aluminum electrodes, inter-electrode spacing ≥ 1 cm, current density ≤ 10 mA/cm², initial pH 6 ≤ pH < 11, electrolysis time < 60 min, batch operation, and initial nickel concentration > 50 mg/L. This comprehensive review serves as a foundational resource for advancing electrocoagulation technology in the removal of heavy metals from nickel wastewater.

Keywords: Electrocoagulation; nickel, wastewater treatment

1. Introduction

Nickel metal is widely used in various industrial and trade sectors, including in stainless steel making, electroplating processes, use in batteries, textile industry, electrical device manufacturing, and as a catalyst in chemical reactions (Kumar and Dwivedi, 2021). Even in recent years, the rampant production of electric vehicles for green energy is projected to continue to increase, which has an impact on the sustainable supply of nickel will be needed as a raw material for electric vehicle batteries. Significant global demand for nickel has driven an increase in its production. According to a United States Geological Survey (USGS) report, in 2019, Indonesia became the largest producer of nickel metal in the world after China with production reaching 487,000 tons per year.

The increasing demand for nickel metal will result in increased extraction of nickel metal from nature. This makes mining and metallurgical processes the main sources of nickel pollution in addition to natural sources such as volcanoes and geological pollution of groundwater. In mining areas, nickel pollution can occur through runoffs that carry heavy metals including nickel and flow into water bodies around the mine site and pollute the environment. Nickel metal has a high water solubility and is *nonbidegradable*, so it can be easily absorbed and accumulated in the body of living organisms and cause serious environmental damage (Xu et al., 2018). The human body can be exposed to nickel through the food chain, especially by consuming nickel-contaminated fish from aquatic environments. The toxicity of nickel depends on the nature of the compound and its pathway of entry into the human body, such as oral, eye, skin, or respiratory pathways. Nickel exposure is an important concern because it can cause various diseases such as respiratory damage, lung cancer, diarrhea, low blood pressure, bone defects, and others (Costa et al., 2022).

Along with technological developments, many techniques have been used to remove nickel metal from wastewater, such as chemical coagulation, adsorption, ion exchange, *reverse osmosis* and membrane filtration (Xu et al., 2018). However, most of these technologies have limitations such as expensive costs, high energy consumption, complex and long processing processes, making nickel metal processing difficult (Merma et al., 2020). Among these processing technologies, the electrocoagulation (EC) process is becoming popular due to its high contaminant removal efficiency, in-situ coagulant production, and larger and stable floc formation compared to conventional coagulation. In addition, the sludge produced in EC may be more stable and less toxic. EC effectively removes a broad spectrum of contaminants and pollutants from various water sources (Biswas and Goel, 2022). In EC technology, the dissolution of metals at the anode produces a metal hydroxide complex, which acts to eliminate colloidal particles by neutralizing the charge. This process also reduces electrostatic repulsive forces and removes dissolved contaminants through the formation of metal ligand compounds and absorption in flocs. At the same time, electro-flotation occurs due to the formation of hydrogen gas bubbles on the surface of the cathode, which causes floc to float to the reactor surface (Apshankar and Goel, 2018; Babu and Goel, 2013; Biswas and Goel, 2022).

Electrocoagulation technology has been widely applied to various types of wastewater, such as acid mine wastewater (Alam et al., 2022 & Stylianou et al., 2022), domestic wastewater (Patel et al., 2022), electroplating wastewater (Wang et al., 2021), baker's yeast wastewater (Alavijeh et al., 2022), metal plating industry wastewater (Xu et al., 2018 & Costa et al., 2022) and slaughterhouse wastewater (Adou et al., 2022). Several studies on heavy metal removal in wastewater using electrocoagulation technology have been published, but no reviews have been found on nickel metal-specific heavy metal removal using electrocoagulation from wastewater. This paper aims to address this gap by reviewing electrocoagulation studies for nickel removal from wastewater. The research objectives include elucidating the contaminant removal mechanism and analyzing factors influencing nickel reduction, with a focus on operational parameters. The contributions of this review lie in consolidating knowledge, providing insights into EC's efficacy for nickel removal, and guiding future research and environmental management efforts.

2. Methods

The database used to search the literature reviewed in this paper was limited to research published in English-language research articles and review articles published from ScienceDirect and can be downloaded through a subscription to the Bandung Institute of Technology (ITB). ScienceDirect is considered the most extensive research database and is often used by researchers around the world. Only research articles and review articles published between January 2013 and July 2023 were considered, both to keep the number of candidate references to a feasible level and because it is only relatively recently that electrocoagulation process has been considered a practically viable method for removal of heavy metals from wastewater, especially nickel metal. The search was conducted as follows: First, each of the databases was queried with the Boolean subject search: ("electrocoagulation"), ("heavy metals"), ("nickel"), ("wastewater" or "effluent" or "industrial wastewater" or "mine water"). This search was intended to capture references focused on using electrocoagulation to remove heavy metals from wastewater, specifically nickel. The specific query was selected by the authors after running a number of preliminary searches to identify terms that returned the greatest number of relevant results. The search yielded 155 references. Second, a screening process was carried out by checking duplicate references and manually reading the title and abstract of the publication to verify whether the literature used electrocoagulation as a treatment technology to remove nickel metal from the original wastewater or artificial wastewater that simulated wastewater, leaving 48 references. Third, the selected literature was filtered based on the merits of the review, and each relevant reference was manually analyzed to identify additional relevant references. The full texts of the candidates were obtained and confirmed for relevance. A total of 32 references were ultimately included in the literature review.

In this study, we collected and analyzed a number of related studies that have been conducted using a variety of waste types as well as diverse waste conditions. In essence, these studies have similarities in the use of electrocoagulation technology as the main method to overcome the problem of heavy metal content in nickel wastewater. Although waste characteristics and environmental parameters vary between these studies, they have a similar goal, which is to utilize electrocoagulation as a solution to remove heavy metals from nickel wastewater. By summarizing the findings of these studies, we seek to provide a more comprehensive understanding of the effectiveness of electrocoagulation technology in addressing the various challenges associated with heavy metal pollution in nickel industrial waste.

A total of 32 references were eventually included in the literature review. A summary of the nickel allowance and the type of wastewater used, the initial concentration of nickel, electrode specifications, current density, wastewater pH, treatment volume, mode of operation, and allowance efficiency are summarized in **Table 1**. The systematic review process is shown in **Figure 1**.

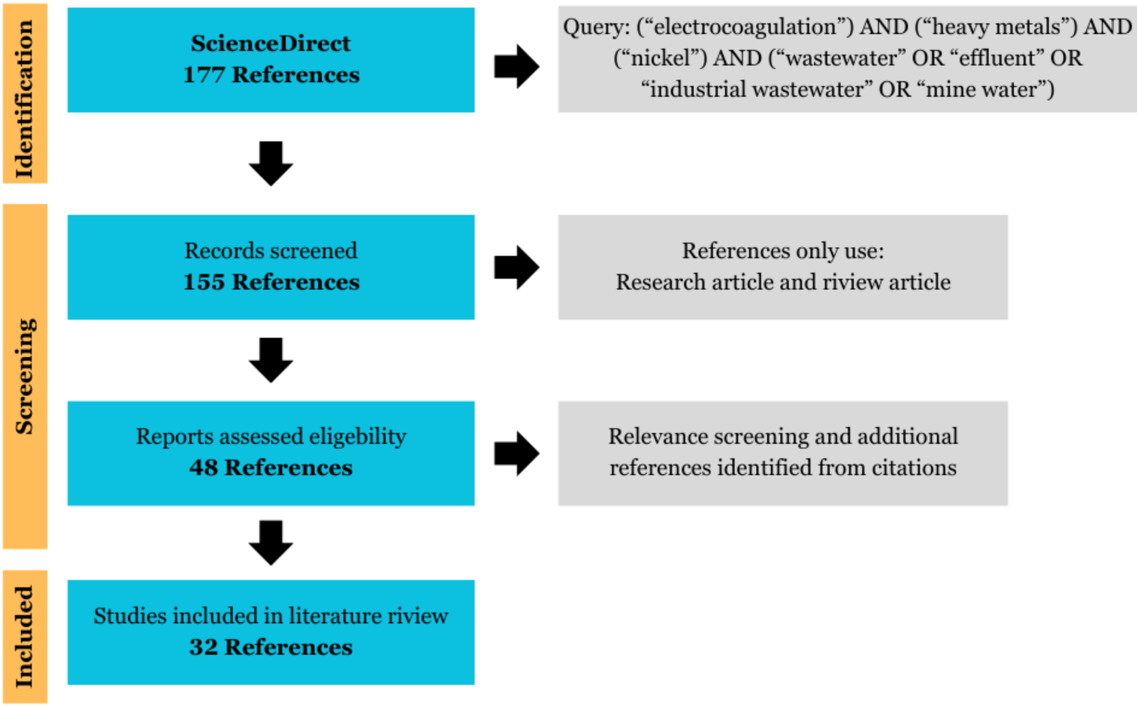

Figure 1. Literature review workflow

Framework

Here is a simple framework describing the main elements in the use of electrocoagulation to cope with nickel waste:

I. Types of Nickel Waste
A. Characteristics of Nickel Waste
- Describe the types of nickel waste present in industrial wastewater.
- Identify sources of nickel waste.

II. Electrocoagulation Regulation
A. Electrode Type Selection
- Choose an appropriate type of electrode for the electrocoagulation process, such as iron or aluminum.

- Reasons for choosing the type of electrode based on the characteristics of nickel waste.

B. Optimal Voltage Current

- Regulates the intensity of the electric current required for electrocoagulation
- Analyze the impact of voltage current variations on nickel metal removal efficiency.

C. Fluid and Electrolyte Concentration

- Control the concentration of liquids and the type of electrolyte used in the process.
- Presents the effect of fluid and electrolyte concentration on the effectiveness of electrocoagulation.

III. The Best Choice in Nickel Waste Handling

- Summarizing the best electrocoagulation arrangements that have been identified for nickel waste removal.
- The present recommendations are based on the research and analysis of the results obtained.

With this framework, you can explore how the selection of nickel waste types and the appropriate electrocoagulation arrangements can be used to achieve the best results in nickel waste management in industrial wastewater. This framework can help identify the most effective and efficient solutions to tackle nickel metal pollution in different contexts.

3. Result and Discussion

3.1 Electrocoagulation Process Illustration

The electrocoagulation process is a method of water or liquid waste treatment that uses electrochemical principles to remove solutes, solid particles, and pollutants from water (Shahedi et al., 2020). This process involves the use of a positive electrode (anode) and a negative electrode (cathode) dipped in water or liquid waste to be treated (Asfaha et al., 2021) as show in **Figure 2**. Several chemical reactions occur when an electric voltage is applied through the electrodes.

- Oxidation: At the anode, oxygen is released, and hydroxide ions are formed. This reaction helps oxidize organic materials dissolved in water.
- Reduction: At the cathode, hydroxide ions reduce heavy metals or other compounds present in the liquid waste.
- Coagulation: Electrochemical reactions also lead to the formation of small solid flocs that can bind to small particles and solutes in water. These flocs became larger and easier to deposit.
- Precipitate: The solid particles that coagulate can then be easily precipitated from water.

These chemical reactions can be sequential and/or parallel. All of them are summarized in **Figure 3** which highlights the complexity and the interplay between the mechanisms of electrocoagulation process. This process helps remove a variety of contaminants from water, including heavy metals, dissolved organic matter, and solid particles. Arrow lines can be used to indicate the electric current flowing between the electrodes, and changes in the color or clarity of water before and after the electrocoagulation process can be illustrated to show improvements in water quality, as shown in **Figure 4**.

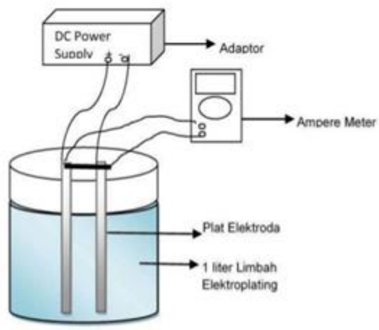

Figure 2. Scheme of electrocoagulation reactor
Source: (Zailani et al., 2018)

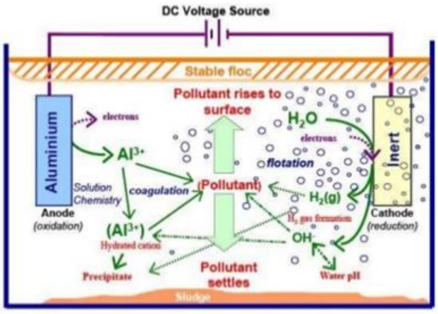

Figure 3. Illustration of electrocoagulation reactions
Source: (Hakizimana et al., 2017)

Figure 4. Before and after the electrocoagulation process (Taty, 2016)

Some electrode materials can be made of aluminum, iron, stainless steel and platinum. In this study, Al was used as the anode material. Equation (1) describes the dissolution of the aluminum anode:

$$Al^{3+} + 3e^{-} \leftrightarrow Al \quad (1)$$

Simultaneously, cathodic reactions usually occur hydrogen changes. This reaction occurs at the cathode and depending on the neutral or alkaline pH, hydrogen is produced through equation (2):

$$2H_2O + 2e^{-} \rightarrow OH^{-} + H_2 \quad (2)$$

When under acidic conditions, equation (3) can best explain the change in hydrogen at the cathode.

$$2H^{+} + 2e^{-} \rightarrow H_2 \quad (3)$$

There are several types of species interactions in solution during the electrocoagulation process, namely:

1. Migration to oppositely charged electrodes (electrophoresis) and aggregation to form neutral compounds.
2. Cations or hydroxy ions (OH^-) form precipitates with pollutants.
3. Metal cations interact with OH to form hydroxy, which has sides that adsorb pollutants (bridge coagulation)
4. Hydroxy forms large structures and clears pollutants (sweep coagulation)
5. Oxidation of pollutants thereby reducing their toxicity
6. Removal by electroflotation and adhesion of air bubbles.

In the electrochemical process, Al3 + is released from the electrode plate (anode) to form floc $Al(OH)_3$, which can bind contaminants and particles in waste. In this reaction, the aluminum ion (Al^{3+}) reacts with three hydroxide ions (OH^-) to form floc aluminum hydroxide ($Al(OH)_3$), which precipitates and binds to particles or contaminants in the waste, as shown in **Figure 5**. This electrochemical process is one of the methods used in sewage treatment, especially in the process of separating particles from waste solutions. The resulting floc can be easily precipitated or removed from the solution, thereby reducing waste contamination and improving the quality of the water or solution produced.

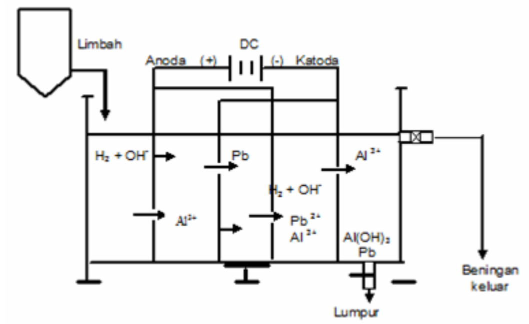

Figure 5. Electrocoagulation process
Source: (Hernaningsih & Yudo, 2007)

If two electrodes are placed in an electrolyte and direct electric current flows, an electrochemical event occurs, which is a symptom of electrolyte decomposition, where positive ions (cations) move to the cathode and receive reduced electrons, and negative ions (anions) move to the anode and give up oxidized electrons (Islam, 2019). The cathode of the H^+ ion of an acid is reduced to hydrogen gas, which is free as gas bubbles.

Coagulation and flocculation are traditional methods of wastewater treatment. In this process, coagulants such as alum or ferry, chloride, and other additives such as polyelectrolytes are added with certain doses to produce compounds with large particles so that they are easily separated physically (Shim et al., 2014). This is a process with many stages so that it requires a large area of land and the availability of chemicals continuously (continuous). A more efficient and inexpensive method to treat wastewater with a variety of pollutant types and minimize additives is needed in water sustainability management. Electrocoagulation is a processing method that is able to answer these problems (Drogui et al., 2007).

3.2 Nickel Removal by Electrocoagulation

Electrocoagulation (EC) is an electrochemical water treatment technology using electrodes that are electrified to produce floc in-situ through electron transfer which includes oxidation, reduction and desposition so that the process of clumping and settling fine particles in water occurs (Nur, A. 2014; Kamal, I. 2018; Ridantami, V. 2021). The electrodes used are usually made of reactive metals, such as aluminum or iron which can act as anodes and cathodes. Electrocoagulation involves several mechanisms, including anodic dissolution, hydrolysis of metal ions, precipitation of metal hydroxides, aggregation of colloidal particles, evolution of hydrogen gas, and flotation (Da et al., 2019). Therefore, EC is able to remove various types of pollutants, such as total suspended solids (TSS), organic matter, phosphates, fluorides, arsenates, and nickels through various means, including adsorption, charge neutralization, coprecipitation, sweep flocculation, and electroflotation (Hasan, F. 2022, Garcia-Segura et al., 2017; Lin et al., 2019; Chen et al., 2020). These advantages make electrocoagulation (EC) an optimal method for wastewater treatment that has a complex composition, such as industrial effluent, geothermal water, and mining wastewater. Recent studies reporting nickel removal using electrocoagulation are summarized in **Table 1**.

Table 1. Nickel metal removal in different types of wastewater

No	Wastewater type	Initial concentration	Electrode combination (A-C)	Inter-electrode distance	Current density/ voltage	Initial pH	Mode operation	EC Time	Wastewater volume	% removal	Reference
1	Industrial effluent	313 mg/L	Al-Al	0.8 cm	6.26 mA/cm²	8.20	Semi-continuous	2 L/min (200 min)	100 L	97.8	Vargas et al., 2023
2	Raw sanitary leachate from landfills	93 µg/L	Al-Al	2 cm	3.47 mA/cm²	9.5	Batch	10 min	12 L	64.5	Genethliou et al., 2023
3	Synthetic wastewater containing (Ni(II)-NH_3-CO2-SO2-H2O)	342 mg/L	Al-Al	0.8 m	11 mA/cm²	8.34	Batch	50 min	25 L	95.6	Vargas et al., 2023
4	synthetic effluent similar to gold mine effluents	65 mg/L	Fe-SS	5 cm	3.75 mA/cm²	10	Batch	60 min	2 L	76.4	Shahedi et al., 2023
5	Synthetic wastewater containing methyl orange, $NiSO_4$, and F^- (NaF)	100 mg/L	He-Fe	1 cm	20 mA/cm²	6	Batch	30 min	0.18 L	>90	Fan et al., 2023
6	Synthetic wastewater containing $ZnSO_4$, NiSO4, CuSO4	2.5 mg/L	SS-SS	1 cm	18.75 mA/cm² 1.5 A	6	Batch	60 min	1.8 L	98.14	Kumar et al., 2022
7	Synthetic wastewater containing Ni	331.9 mg/L	Al-Al	1 cm	8 mA/cm²	8	Batch	37.5 min	1 L	94.52	Arabameri et al. 2022
8	Real industrial electroplating rinsing wastewater	20.01 mg/L	SS-SS	2 cm	10 Volt	9	Continuous	30 min (100 mL/min)	10 L	98.9	Abdel-Shafy et al., 2022
9	Real acid mine drainage (AMD) of copper mine	0.134 mg/L	Al-Al	0.5 cm	20 mA/cm²	2.6	Batch	150 min	0.5 L	98	Stylianou et al., 2022
10	Synthetic wastewater containing (Ni(II)-NH_3-CO2-SO2-H2O)	505 mg/L	Al-Al	1 cm	9.8 mA/cm²	8.6	Batch	30 min	0.5 L	99.5	Vargas et al., 2022
11	Synthetic industrial wastewater containing Ni	250 mg/L	Al-Al	0.5 cm	0.95 mA/cm²	6	Batch	30 min	10,5	75.99	Fil et al., 2022
12	Liquid waste from spent-battery recycling containing heavy metal	8.91 mg/L	Al-Al	1 cm	25 mA/cm²	12.23	Batch	30 min	0.5 L	>99.5	Mufakhir et al., 2022
13	electroplating wastewater	-	SS-SS	2 cm	30 mA/cm²	4	Batch	70 min	0.25 L	82%	Liu et al., 2021

No	Wastewater type	Initial concentration	Electrode combination (A-C)	Inter-electrode distance	Current density/ voltage	Initial pH	Mode operation	EC Time	Wastewater volume	% removal	Reference
14	Real wastewater of ore washing from crushing screening plant	10.3 mg/L	He-Fe	1.5 cm	16 mA/cm^2	8.5	Batch	40 min	0.5 L	90.23	Altunay et al., 2021
15	Synthetic wastewater containing heavy metals	100 mg/L	Al-Al	1 cm	1.72 mA/cm^2	4	Batch	40 min	1.4 L	100	El-Ashtoukhy et al. 2020
16	Synthetic electroplating wastewater	70.524 mg/L	Al-Al	2 cm	7.79 mA/cm^2	8.5	Batch	50 min	15 L	99,7	Moersidik et al. 2020
17	Synthetic electroplating wastewater	111.3 mg/L	Al-Gr	-	1.5 A	4.8	Batch	10 min	0.2 L	88.68	Huang et al., 2020
18	Synthetic metal plating wastewater	20 mg/L	He-Fe	1 cm	4 mA/cm^2	11	Batch	60 min	0.5 L	95	Kim et al. 2020
19	Real mine water	9.28 µg/L	He-Fe	-	18 mA/cm^2	6.5	Batch	60 min	1 L	97	Mamelkina et al., 2019
20	Synthetic wastewater	100 mg/L	Al-Al	2 cm	6 Volt	7.5	Batch	20 min	0.2 L	78	Jerroumi et al., 2019
21	Real wastewater of metal plating	8.1 mg/L	He-Fe	3 cm	45 mA/cm^2	5	Batch	30 min	0.5 L	96	Oden and Sari-Erkan 2018
22	Effluent of an electroplating plant in Bandung City, Indonesia	10.523 mg/L	Al-Cu	5 cm	5 Volt	3.4	Batch	90 min	0.5 L	14.8	Djaenudin et al. 2018
23	Real flue gas desulfurization wastewater	3.37 mg/L	Fe-C-Al	0.5 cm	5 A	4	Batch	25 min	1 L	98	Liu et al., 2017
24	Real wastewater containing Ni-EDTA	7.82 mg/L	Fe-SS	10 cm	0.5 A	3	Batch	30 min	0.45 L	95.14	Ye et al., 2016
25	Real wastewater of metal plating	57.5 mg/L	He-Fe	1.5 cm	4 mA/cm^2	9.5	Batch	45 min	0.6 L	98	Al-Shannag et al., 2015
26	Real waste fountain solution	1.7 mg/L	Faith-Al	1.5 cm	8 mA/cm^2	5	Batch	60 min	0.22 L	95	Prica et al., 2015
27	Synthetic wastewater containing Ni	100 mg/L	Al-Al	1 cm	22.5 mA/cm^2	6	Continuous	25 min	0.12 L	>90	Lu et al., 2015
28	Wastewater of electroplating industry	16.30 mg/L	Al-Al	1 cm	12 Volt	8.15	Batch	210 min	1.8 L	88.2	Lekhlif et al., 2014

No	Wastewater type	Initial concentration	Electrode combination (A-C)	Inter-electrode distance	Current density/ voltage	Initial pH	Mode operation	EC Time	Wastewater volume	% removal	Reference
29	Synthetic bilge water	1.5 mg/L	Al-Al	-	6 mA/cm^2	-	Continuous	0.5 L/min	45 L	92.7	Rincón and La Motta, 2014
30	Real wastewater of effluent metal plating	165 mg/L	Fe-SS	0.6 cm	90 mA/cm^2	9	Batch	60 min	0.61 L	100	Beyazit et al., 2014
31	Synthetic wastewater	100 mg/L	Al-Al	4 cm	72.5 mA/cm^2	5	Batch	180 min	1 L	90	Vlachou et al., 2013
32	Synthetic wastewater	-	He-Fe	2.5 cm	12 Volt	7	Batch	10 min	1.5 L	97.6	Khosa et al., 2013

3.3 Electrode Type

The efficiency of Ni metal removal using EC technology depends largely on the selection of the electrode materials used. Electrode selection is based on consideration of existing contaminants, desired wastewater quality, cost, and oxygen evolution potential (Biswas B and Goel S., 2022). Based on the review conducted, it was found that there are four types of electrodes most commonly used in the EC process to remove nickel metal from wastewater. These types of electrodes include aluminum (Al-Al), iron (Fe-Fe), stainless steel (SS-SS), and combination electrodes (Fe-Al, Fe-SS, Fe-Cu, etc.) as shown in **Table 1**. Based on the results of the 32 studies analyzed in **Table 1**, the percentage of the number of studies with the use of each type of electrode is shown in **Figure 6**.

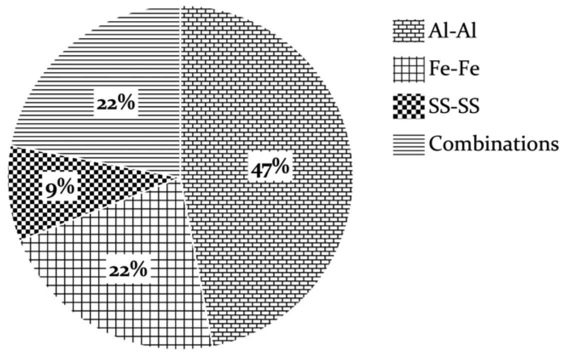

Figure 6. Percentage of the amount of research in the use of this type of electrode

Based on **Figure 6**, it can be seen that the type of electrode with the largest percentage is aluminum, which is present in 47% of studies. This shows that aluminum is the most common type of electrode used in the removal of nickel metal from wastewater because it has a good level of removal efficiency. For example, it was noted that the lowest nickel metal removal reached 64% in synthetic wastewater (Genethliou et al., 2023), while the highest nickel metal removal reached 100% in synthetic wastewater with an initial concentration of 100 mg/L (El-Ashtoukhy et al., 2020).

Aluminum electrodes perform well in nickel metal removal because they produce hydrolyzed species containing Al(III). This species has a more effective ability to disrupt nickel metal particles, thus aiding in the process of deposition and separation of the metal from wastewater. The high valence charge of Al(III) in hydrolyzed species of aluminum electrodes allows for a denser electric bilayer. This significantly increases the ability of electrocoagulation to coagulate nickel metal particles. Consequently, larger flocs form and are easier to filter or deposit. In addition, aluminum also follows Faraday's law in terms of dissociation estimates. This property makes it easier for aluminum electrodes to predict their performance than other electrodes, such as iron. The high solubility of aluminum species in electrolyte solutions also plays a role in providing consistency and reliability of aluminum electrode performance (Zaied et al., 2020).

Based on the analysis of the review literature **(Table 1),** it was found that the use of electrode types in the process of removing nickel metal from wastewater is still limited to the four types of electrodes mentioned earlier. Therefore, further research is needed involving the use of other types of electrodes, such as magnesium and galvanized iron, which may have potential advantages in terms of cost, efficiency, and other factors that may provide advantages in the process.

3.4 Distance Between Electrodes

The distance between the electrodes is a control parameter in the design of the reactor for the removal of nickel metal from wastewater. In the process of electrocoagulation, the electrostatic field generated depends on the distance between the anode and cathode. Therefore, to achieve maximum nickel metal removal efficiency, it is important to maintain the distance between the electrodes in optimal conditions. In this study, the distance between the electrodes was divided into two categories: < 1 cm and ≥ 1 cm. This was done to see the trend of using the distance between electrodes that are most widely used in electrocoagulation processes to remove nickel metal from wastewater. The percentage of the number of studies with the use of each distance between electrodes can be seen in **Figure 7**, while more detailed information can be found in **Table 1**.

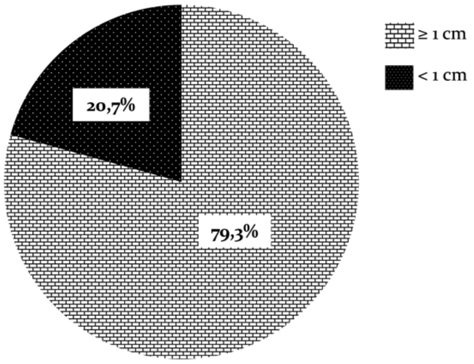

Figure 7. Percentage of the amount of research in the use of distance between electrodes

Based on **Figure 7**, it can be seen that there are as many as 79.3% of studies that use the distance between electrodes with a size of ≥ 1 cm with a range of 1-10 cm. While the remaining 20.7% of studies used a distance between electrodes with a size of < 1 cm with a range of 0.5-0.8 cm. From this literature review, it can be seen that the use of distances between electrodes with a size of < 1 cm and ≥ 1 cm both have good removal efficiency. For example, in the study of Fill, B. A. (2022), a distance between electrodes of less than 1 cm was used, which is 0.5 cm, which resulted in a nickel metal removal efficiency of 75.99% in artificial wastewater with an initial concentration of 250 mg/L. Meanwhile, the distance between the electrodes ≥ 1 cm, which is 10 cm, resulted in a nickel metal removal efficiency of 95.14% in original wastewater containing Ni-EDTA with an initial concentration of 7.82 mg/L (Ye, X. et al., 2016).

The reason why most researchers use the distance between electrodes with a size of ≥ 1 cm is because the efficiency of pollutant removal increases with increasing the distance between the electrodes from the "minimum distance" to the "optimum distance". This happens because as the distance between the electrodes increases, the electrostatic effect decreases and results in slower movement of ions. This provides more time for the resulting metal hydroxide to coagulate and form flocs, which increases the efficiency of pollutant removal in solution. However, if the distance between the electrodes is too large from the "optimum distance", the efficiency of pollutant removal will decrease. This is because the time it takes for the ions to reach the electrode increases as the distance between the electrodes increases. As a result, electrostatic attraction is reduced and floc formation required to agglomerate pollutants is also reduced (Aoudj et al., 2015).

While the reason fewer researchers use the distance between electrodes with a size of < 1 cm is because the narrow distance between electrodes can cause low pollutant removal efficiency. This is due to the fact that the resulting metal hydroxide which acts as floc to remove pollutants through sedimentation, degrades due to collisions between metal hydroxide particles with one another due to high electrostatic attraction (Aoudj et al., 2015). In addition, the narrow distance between electrodes can cause a short circuit because the current density becomes too high (Fekete et al., 2016).

Therefore, further research is needed to determine the optimal distance between the electrodes to remove nickel metal from wastewater. Because the optimal distance between electrodes can vary depending on the type of electrode used, the type of particles to be deposited, and other operational parameters. For example, wastewater with relatively high conductivity, the use of a larger distance between electrodes can reduce energy consumption (at a constant current density). On the other hand, wastewater with low conductivity, the use of smaller distances between electrodes can minimize energy consumption (Bazrafshan et al., 2015).

3.5 Current Density

Current *density* in the electrocoagulation process refers to the amount of electric current that flows through the electrode surface area unit submerged in water or solution to be treated (mA/cm²). Current density plays an important role in the electrocoagulation process because it affects coagulant dose, bubble production, size, and increase in floc number which can affect EC efficiency (Bazrafshan et al., 2015). According to Faraday's law, with an increase in current density, the rate of dissolution of the anode increases. This leads to an increase in the number of metal hydroxide flocs, which results in an increase in the efficiency of pollutant removal. In addition, the rate of formation of H_2 bubbles also increases with increasing current density, whereas the size of the bubbles tends to shrink (Holt et al., 2004). Current density values were grouped into four categories: ≤ 10 mA/cm², 10 < mA/cm² ≤ 20, 20 < mA/cm² ≤ 30, and > 30 mA/cm². It aims to identify trends in the use of optimal current density in the removal of nickel metal from wastewater. The percentage of studies using each category of current density values is shown in **Figure 8**, while more detailed information on the effect of current on the removal of nickel metal from wastewater can be found in **Table 1**.

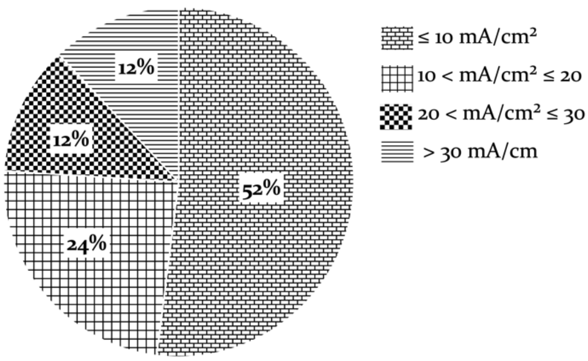

Figure 8. Percentage of the amount of research in the use of current density

From the analysis shown in **Figure 8,** it can be observed that the use of a current density of ≤ 10 mA/cm² is the most commonly used in studies of nickel metal removal from wastewater, accounting for 52% of the total studies analyzed. These results indicate that relatively low current densities are still considered effective in removing nickel metal from wastewater. Several studies have reported optimal current density values for electrocoagulation processes in the removal of nickel metal from wastewater (Vargas et al., 2023; Shahedi et al., 2023; Arabameri et al., 2022; Liu et al., 2021). As the current density increases, the time required to remove nickel metal tends to decrease. The effect of current density on nickel metal removal has been studied previously (Fil et al., 2022). Nickel metal removal efficiencies of 58.29%, 68.71%, 75.99%, and 92.38% were achieved within 30 minutes electrolysis time with current density values of 0.24, 0.48, 0.95, and 1.43 mA/cm² respectively.

Furthermore, current densities of 10 < mA/cm² ≤ 20 are also quite commonly used in studies of nickel metal removal from wastewater, accounting for 24% of the total research. These results indicate interest in exploring slightly higher current densities in order to improve the efficiency of nickel metal removal. However, keep in mind that the effectiveness of using current density in this range still depends on other operational parameters such as temperature, pH, electrode distance, and mixing speed (Chen, 2004; Moussa et al., 2017).

Meanwhile, the use of current densities of 20 < mA/cm² ≤ 30 and > 30 mA/cm² had a lower percentage of research, each of which was 12% (**Figure 8**). These results suggest that the use of higher current density values tends to be used less frequently in the context of nickel metal removal from wastewater. This is because the use of very high current densities can cause several problems, such as coagulant overdose, high energy consumption, and electrode passivation. Coagulant overdose can lead to the restabilization of particles present inside the reactor because of the reversal of charge from negative to positive on the particle surface, which can ultimately result in decreased efficiency in pollutant removal (Biswas and Goel., 2022).

An increase in current density above the optimum value does not provide a significant increase in efficiency in pollutant removal. This is because at higher current density values, the amount of metal hydroxide floc produced is sufficiently available for the pollutant sedimentation process (Vik et al., 1984; Bukhori, 2008; in Bazrafshan et al., 2015). Therefore, increasing the current density above the optimum value will only increase energy consumption without providing significant benefits in pollutant removal efficiency. This is in line with the results of previous research conducted by Altunay et al. (2021), where the efficiency of nickel metal removal only increased until it reached an optimum current density of 21.3 mA/cm^2 with an allowance rate of 98.14%. However, at higher current densities, there was a decrease in the allowance efficiency from 98.14% to ±93% at a current density of 42.67 mA/cm^2.

The selection of the right current density is very important in the process of electrocoagulation. A current density that is too low may not be enough to trigger the necessary electrochemical reactions, while a current density that is too high can cause unwanted electrolysis effects, such as particle restabilization, excess gas formation or short circuit. Therefore, it is necessary to regulate the current density according to specific conditions to achieve optimal results in the electrocoagulation process.

3.6 Initial pH

Initial pH is an important operating factor affecting electrocoagulation performance and plays an important role in the removal of nickel metal in wastewater. This is because the formation of metal hydroxide floc which acts as a coagulant agent in the electrocoagulation process is strongly influenced by the pH of the solution. At lower pH (less than 4), cationic species such as Al^{3+} and $Al(OH)^{2+}$ are dominant, but at mid-range pH (4 to 9), some monomer species such as $Al(OH)^{2+}$, and polymer species, namely, $Al_6(OH)_{15}^{3+}$, $Al_7(OH)_{14}^{4+}$, $Al_{13}(OH)_{34}^{5+}$ are more dominant which eventually turn into aluminum hydroxide removal agents ($Al(OH)_3$). At higher pH (greater than 10), cathodic corrosion occurs, and the concentration of $Al(OH)_4^-$ increases at the expense of the removing agent (aluminum hydroxide) (Bayramoglu et al., 2003; Alinsafi et al., 2004; Merzouk et al., 2009 in Arabameri et al., 2022). Choosing the right pH can optimize the formation of large, dense flocs, which in turn allows for more effective deposition of pollutants (Biswas and Goel., 2022). In this literature study, the initial pH value was grouped into three categories, namely 1 ≤ pH < 6, 6 ≤ pH < 11 and 11 ≤ pH ≤ 14 . The aim was to identify the trends in the optimal use of the initial pH for the removal of nickel metal from wastewater using the electrocoagulation method. The percentage of the number of studies with the use of each initial pH can be seen in **Figure 9**, while more detailed information can be found in **Table 1**.

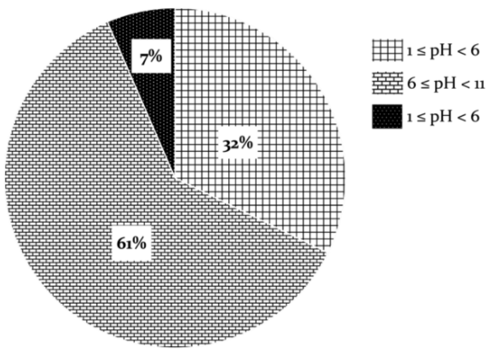

Figure 9. Percentage of the amount of research in the use of initial pH

From the analysis shown in **Figure 9,** it can be observed that the use of initial pH in the range of 6 ≤ pH < 11 is the most widely used in studies of nickel metal removal from wastewater, accounting for 61.3% of the total studies analyzed. These results indicate that an initial pH that is relatively neutral to slightly alkaline is considered effective in removing nickel metal from wastewater. Several studies have reported optimal initial pH values for electrocoagulation processes in nickel metal removal from wastewater (Vargas et al., 2023; Fil et al., 2022; Altunay et al., 2021). The effect of initial pH on nickel metal removal has been studied previously (Arabameri et al., 2022). The results obtained in this study, reported an evolution in nickel removal efficiency from 75.73% to 96.87% by increasing the initial pH from 5 to 9 at a concentration of 300 mg/L with a current density of 7 mA/cm^2.

Based on the results of research conducted by Arabameri et al., (2022) states that the optimal performance of the electrocoagulation system for nickel removal occurs in the initial pH range of around 7 to 9. In this pH range, the dominant removal mechanism is adsorption by aluminum hydroxide ($Al(OH)_3$), and the joint removal mechanism is precipitation by hydroxide ions (OH^-) in the form of $Ni(OH)_2$. Adsorption by aluminum hydroxide allows the capture and separation of nickel particles from solution, while precipitation by hydroxide ions results in the formation of insoluble $Ni(OH)_2$ precipitate. These two mechanisms work synergistically to improve the efficiency of nickel removal in the electrocoagulation process. During the electrocoagulation process, the initial pH of the solution gradually increased owing to the production of hydroxide ions (OH^-) at the cathode.

Furthermore, the initial pH with a range of $1 \leq pH < 6$ is also quite commonly used in research on nickel metal removal from wastewater, accounting for 32.3% of the total research. These results indicate interest in exploring the initial pH classified as acidic in order to improve the efficiency of nickel metal removal. Liu, et al., (2021) studied nickel metal removal from electroplating wastewater using EC and found that the pH of the solution has a significant influence on the removal efficiency of Ni^{2+}. They conducted experiments at different pHs in the pH range of 1, 2, 3, 4, 5, 6, 7, and 8. The results showed that the nickel removal efficiency increased from 42% to 78% by increasing the initial pH from 1 to 4. However, there was a decrease in efficiency from 78% to 67% by increasing the initial pH from 4 to 8. Maximum nickel removal efficiency is obtained at pH 4. It can be implied that the efficiency of nickel removal is reduced by increasing or lowering the pH of the solution from the optimum pH.

Meanwhile, the use of initial pH with a range of $11 \leq pH \leq 14$ has a lower percentage of research of 6.5% (**Figure 9**). This pH range is categorized as extremely alkaline. These results suggest that the use of higher initial pH values is less likely to be used in the context of nickel metal removal from wastewater. This is because the use of very high initial pH can cause several problems, such as increased concentrations of $Al(OH)^-_4$, high corrosion potential, and electrode passivation. At very high pH conditions, there is an increase in hydroxide ion (OH^-) concentration, which leads to the formation of the more dominant $Al(OH)^-_4$ complex. As a result, the formation of metal hydroxide flocs, such as $Al(OH)_3$, becomes more difficult. $Al(OH)_3$ acts as a coagulant agent that is effective in removing nickel metal from solution. However, at very high pH, the formation of large, dense floc becomes difficult, so the flocculation and deposition ability of pollutant particles is inhibited (Arabameri et al., 2022). This condition is the same as the results obtained in the study of Shahedi et al. (2023) reported that by increasing the pH from 10 to 12, the nickel residual concentration increased from 45 mg / L to 61 mg / L with an initial concentration of 56 mg / L.

3.7 Electrolysis Time

Electrolysis time can significantly affect the processing efficiency of the electrocoagulation process (Esfandian et al., 2017). The pollutant removal efficiency increases as the electrolysis time is extended, but after reaching the optimal electrolysis time, the pollutant removal efficiency stabilizes and does not increase further. This process involves the formation of metal hydroxides through anode dissolution and cathode reduction. Under conditions of a fixed current, an increase in electrolysis time leads to an increase in the amount of metal hydroxide, OH^-, and H_2 bubbles produced. Longer electrolysis times result in the absorption of more contaminants by hydroxyl ions, resulting in improved floc formation and pollutant removal efficiency. However, given a longer electrolysis time than the optimum electrolysis time, the pollutant removal efficiency does not increase because the floc supply is sufficient, it can even cause the electrode to become passive due to a long duration of time, leading to a decrease in the pollutant removal rate. Although the increase in electrolysis time slightly increases the effectiveness of the allowance, it is not always applied due to high energy consumption in addition to electrode consumption. Given the maintenance costs and process efficiency, it is necessary to determine the optimum electrolysis time. In addition, increased conductivity can increase the current passing through the cell and the rate of pollutant removal. Therefore, the electrolysis time required to achieve the desired removal efficiency becomes shorter (Biswas and Goel., 2022; Titchou et al., 2021; Zaied et al., 2020, Bazrafshan et al., 2015,). In this review literature, electrolysis time is divided into two categories, namely < 60 and ≥ 60 minutes. This was done to see the trend of using electrolysis time which is most widely used in the electrocoagulation process to remove nickel metal from wastewater. The percentage of the number of studies with the use of each electrolysis time can be seen in **Figure 10**, while more detailed information can be found in **Table 1**.

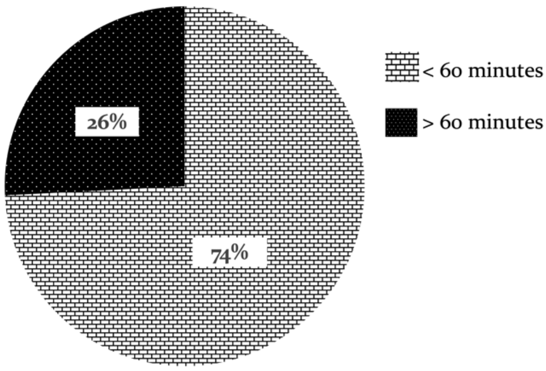

Figure 10. Percentage of the amount of research in the use of electrolysis time

Based on **Figure 10,** it can be seen that most studies (74.2% of the total 32 studies analyzed) tend to use electrolysis time < 60 minutes with a range of 10-60 minutes. This shows that the efficiency of Ni allowance reaches the optimal level in that time span. In addition, the use of a shorter electrolysis time (< 60 minutes) will result in lower consumption of electrodan and electrical energy so that it is in great demand to reduce costs, so in addition to the faster allowance process, costs are also more muran. However, it must still be considered that not under all conditions the optimum electrolysis time is achieved in the range of 10-60 minutes (< 60 minutes), which is very dependent on the conditions of initial concentration and current density. For example, Vergas et al. (2022) investigated the effect of electrolysis time on nickel removal. Different electrolysis times of up to 50 minutes were tested with a Ni concentration of 342 mg/L, an applied current density of 211 mA/cm^2, at pH 8.34. The results showed that the use of an electrolysis time of 50 minutes (< 60 minutes) was able to produce a maximum nickel removal rate of 99.7%, with lower energy consumption of 16.86 kWh/kg Al^{3+}, 2.438 kWh/kg Ni and an adsorption capacity of 5,819 mg Ni/g Al^{3+}. In the same context, Liu, Y. et al. (2021) evaluated the effect of reaction time on electroplating wastewater treatment containing Ni. Increasing the electrolysis time from 10 to 60 minutes increases the removal efficiency from 44% to 79% using a current density of 30 mA/cm^2, pH 4 and aluminum electrode.

As for the use of electrolysis time > 60 minutes, it only covers 25.8% of all studies that have been analyzed (**Figure 10).** This phenomenon illustrates the low interest in the use of long electrolysis times, because the longer the duration of electrolysis needed to achieve optimal conditions, the greater the cost required. This is due to the increase in electrode consumption and electrical energy over time electrolysis, which directly impacts the increase in operational costs. Moreover, if the electrolysis time passes through optimal conditions, the efficiency in the removal of pollutant metals tends to be constant and may even decrease due to electrode passivation due to prolonged use. Therefore, if researchers want to improve the efficiency of elimination, it is advisable to avoid electrolysis time variations exceeding 60 minutes in order to reduce electrode consumption and high electrical energy, which can result in a significant increase in operational costs. An alternative solution is to add electrolyte or modify the pH of wastewater, which may accelerate the achievement of optimal electrolysis time conditions without sacrificing high electrode consumption and electrical energy. The increase in conductivity has the potential to increase the current passing through the cell as well as increase the rate of pollutant removal. Therefore, the electrolysis time required to achieve the desired removal efficiency becomes shorter (Titchou et al., 2021).

3.8 Operation Mode

The electrocoagulation (EC) process has become a promising method in wastewater treatment to address heavy metal contamination, including nickel. This method involves the use of electrochemical reactions to coagulate and precipitate dissolved or dispersed particles in wastewater. In the context of EC usage, there are two operating modes that are commonly used, namely batch operation mode and continuous operation mode. The batch operation mode involves treating a limited amount of wastewater at one specific time period, while the continuous operation mode involves the continuous flow of wastewater through an electrocoagulation cell. These two modes of operation have their own advantages and disadvantages, depending on the purpose of processing and the existing operational conditions. In this review literature, operating modes are classified into two groups, namely batch and continuous. This separation aims to identify the dominant trend in the use of operating modes in electrocoagulation processes in removing nickel metal from wastewater. The percentage of studies adopting each mode of operation can be found in **Figure 11**, while more details are found in **Table 1**.

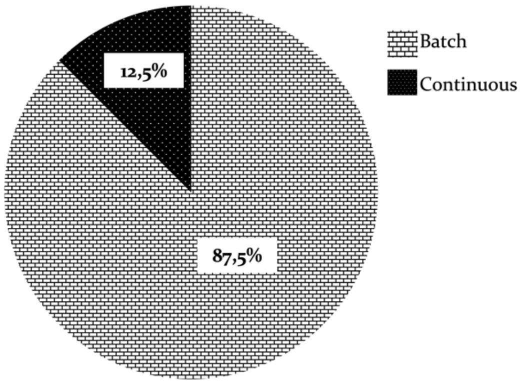

Figure 11. Percentage of the amount of research in the use of operating modes

Based on the analysis of the results shown in **Figure 11**, it can be seen that the batch operation mode has a significant proportion, reaching 87.5% of the total 32 studies. This indicates that in electrocoagulation studies to remove nickel metal from wastewater, the most widely adopted mode of operation is batch. In batch operation mode, the electrocoagulation process is carried out in a single stage where a wastewater sample is fed into an electrocoagulation cell, processed for a certain period, and then stopped upon reaching the desired conditions. The batch operation mode is often chosen by researchers during the nickel removal phase due to its simple installation, flexible batch reactor dynamics, as well as its ability to observe a wide range of operational conditions that are particularly suitable for laboratory-scale research (Mohora et al., 2012; Khandegar and Saroha, 2013; Kobya et al., 2013; Song et al., 2017). There are also reports showing that in batch-type electrocoagulation reactors, investigations regarding factors affecting efficiency (such as concentration, pH, electric current, processing time, etc.) give more accurate results compared to continuous-type reactors (Kobya et al., 2013; Islam, S. D. U. 2023). Another advantage of batch reactors is their ability to be used in decentralized treatment systems, which is particularly useful in rural areas with small volume water treatment needs. Batch reactors allow the treatment of a fixed volume of water in each cycle. In addition, the study of parameters that change over time is easier to do in a batch reactor. In the electrolysis process, coagulants are formed continuously through dissolution of the anode, resulting in pollutant removal and changes in the pH of the solution over time (Shokri and Fard., 2022 & Biswas and Goel., 2022).

In contrast, based on the data shown in **Figure 11**, the use of continuous operation mode only reached a percentage of 12.5% of the total 32 studies. These results indicate that although still relatively rare, continuous operation mode is still used in some studies to overcome nickel metal pollution in wastewater. The continuous mode of operation involves the continuous flow of wastewater through an electrocoagulation cell over a period of time. EC systems with continuous flow operation mode operate in steady conditions, especially at static concentrations and flow rates without time lag, making them a more suitable choice for the treatment of large volumes of waste on an industrial scale. This approach provides benefits in the form of reduced electrolysis time, reduced operational costs, more efficient energy consumption, and reduced sludge formation. The removal efficiency of nickel metal can also be managed more effectively in this system thanks to the ability to pre-optimize operational conditions (Khandegar and Saroha., 2013; Bazrafshan et al., 2015; Sandoval et al., 2021; Islam, S. D. U. 2023). Overall, although the design and operation of continuous EC systems may be more complex, continuous mode of operation has the potential for more efficient treatment and is more suitable for industrial applications that require continuous wastewater treatment. This advantage arises because the continuous mode of operation is more suitable and economically feasible for large-scale operations. Several studies examined nickel removal using a continuous mode of operation. As with previous research, a continuous flow system was applied to set aside oil and heavy metal emulsions (copper, nickel, and zinc) in vessel wastewater. A flow rate of 0.5 L/min was kept constant during the experiment, and a current density of 10 Amperes was applied. The results of this study showed that the efficiency of nickel removal reached 92.5% using aluminum electrodes (Rincón and La Motta, 2014).

The reason for the limited research on continuous mode of operation may lie in several factors. One is the complexity of application which is generally associated with a larger scale, as well as the challenge of controlling the variables involved. This may contribute to the lack of publications or research reviewing the continuous mode of operation, as its success requires a greater allocation of funds and various other resources. Not only that, continuous operation mode is often applied after achieving optimal results from experiments in batch operation mode which of course takes time and a fairly long process. Based on the above explanation, several factors may influence the choice of mode of operation in electrocoagulation research, including the type and volume of wastewater treated, treatment objectives, expected efficiency, resource availability, and technical capabilities. Batch operation mode tends to be more suitable for laboratory-scale research or initial experiments, while continuous operation mode can be more suitable for implementation on an industrial scale.

3.9 Initial Concentration

In the context of the application of EC for the elimination of nickel metal from wastewater, one of the main factors affecting the effectiveness of the process is the initial concentration of nickel in the waste sample. The effectiveness of pollutant removal tends to decrease as the initial concentration increases at a fixed current density. This happens because the amount of metal ions produced remains constant at an unchanged current density during the EC process. As a result, when pollutant concentrations are higher, metal hydroxide production may be insufficient to form adequate clumps of pollutant molecules in the sample. In addition, higher initial concentrations can also extend processing time. Therefore, to remove pollutants with high initial concentrations, a higher quantity of coagulant species is required, which can be achieved through an extension of the electrolysis time or an increase in the applied current (Biswas and Goel., 2022 & Islam, S. D. U. 2023).

This is in line with previous research on nickel removal in synthetic industrial wastewater containing Ni. This study involved an aluminum electrode at a constant current density of 0.95 mA/cm^2, pH 6, and an electrolysis time of 30 minutes. The results of this study noted that an increase in the initial concentration from 25 to 1000 mg/L resulted in a gradual decrease in nickel removal efficiency. This efficiency decreased from 95.34% (initial concentration 25 mg/L) to 91.18% (50 mg/L), 86.72% (100 mg/L), 75.99% (250 mg/L), 62.33% (500 mg/L), to 45.09% (1,000 mg/L) (Fil et al., 2022).

In this research literature, the initial concentration of nickel (Co) is grouped into three categories, namely Co ≤ 1 mg/L, 1 < Co ≤ 50 mg/L, and Co > 50 mg/L. This grouping was carried out to identify the dominant trend in the use of initial concentrations of nickel in the electrocoagulation process in removing nickel metal from wastewater. In addition, we will also discuss how variations in the initial concentration of nickel in EC applications can affect the efficiency of nickel metal removal from wastewater. The percentage of studies adopting each of the initial nickel concentration categories can be found in **Figure 12**, while more detailed information can be accessed in **Table 1**.

Based on the results of the analysis in **Figure 12**, it can be seen that the use of initial concentrations of nickel in the range of Co ≤ 1 mg/L is present in 10% of the total 30 studies analyzed. This indicates that although the number of studies using very low initial concentrations of nickel is relatively small, attention to the treatment of low-concentration waste remains a consideration in the application of EC. The elimination efficiency of nickel metal may reach high levels in this range, as observed in previous studies. For example, in electrocoagulation treatment

\for Real Acid Mine Drainage (AMD) from copper mining with an initial concentration of 0.134 mg/L, the elimination efficiency reached 98% by reaching a final concentration of 0.0027 mg/L at a current strength of 20 mA/cm², pH 2.6, and an electrolysis time of 150 minutes using aluminum electrodes (Stylianou et al., 2022). Despite the high efficiency, it is important to consider the practical limitations of these results, given that very low nickel concentrations may be less common in industrial contexts. Despite the high efficiency, the application of EC on an industrial scale may be challenging due to this very low initial concentration of nickel.

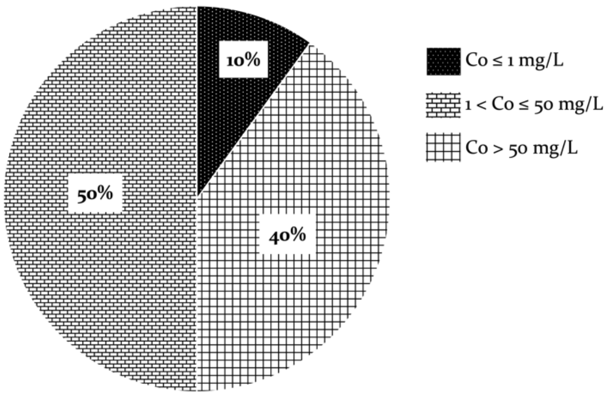

Figure 12. Percentage of the amount of research in the use of Initial Concentration

Meanwhile, in the range of 1 < Co ≤ 50 mg/L, the percentage of utilization of the initial concentration of nickel is high, reaching 40% of the total 30 studies analyzed. This suggests that most studies tend to use samples with moderate concentrations of nickel, representing more realistic conditions in a variety of industries or common domestic environments. Analysis of the data in **Table 1** reveals that the elimination efficiency of nickel metal tends to be optimal in this range. For example, in electrocoagulation treatment for Real Wastewater of Metal Plating with an initial concentration of 8.1 mg/L, elimination efficiency reaches 96% at a current strength of 45 mA/cm², pH 5, and electrolysis time of 30 minutes using iron electrodes (Oden and Sari-Erkan., 2018).

Furthermore, the initial concentration of nickel > 50 mg/L had the highest percentage, covering 50% of the total 30 studies. This shows that electrocoagulation has been widely applied to remove nickel metal in wastewater with high concentrations. Thus, electrocoagulation has the potential to be used in industrial waste with severe levels of pollution. For example, in a previous study, the use of electrocoagulation in a batch system with aluminum electrodes was able to remove nickel with a very high concentration, which is 331.9 mg/L in Synthetic Wastewater containing Ni. This study achieved elimination efficiency of 94.51% by reaching a final concentration of 18.2 mg/L at a current strength of 8 mA/cm^2, pH 8, and electrolysis time of 37.5 minutes (Arabameri et al. 2022).

3.10 Coagulation Treatment Potential

Coagulation treatment, particularly in the form of electrocoagulation, can be used to remove nickel metal from industrial wastewater. The result of the electrocoagulation process can be measured in terms of the amount of nickel metal successfully removed or attached to the cathode. Here is a detailed description of the potential electrocoagulation treatment and how to measure the results:

Electrocoagulation Treatment Potential for Nickel Metal Removal

1. **Electrocoagulation Process Regulation**
   - Determine the type of electrode to use, such as iron or aluminum electrodes.
   - Adjusts the voltage current applied to the electrodes.
   - Set parameters such as processing time and electrolyte concentration if needed.
2. **Electrocoagulation Process**
   - Regulates the flow of wastewater through an electrocoagulation cell containing electrodes.
   - When an electric current is activated, an electrochemical reaction takes place at the electrode that results in the formation of solid flocs.
   - Nickel metal particles in wastewater will interact with the floc of solids formed.
3. **Yield Measurement**
   - Measures the amount of nickel metal attached to the cathode as an indicator of removal effectiveness.
   - It can be measured by calculating the weight of nickel metal collected at the cathode in units of grams per unit of time (for example, grams per minute).
4. **Qualitative Analysis**
   - In addition to quantitative measurements, qualitative analysis can also be performed to examine the extent to which nickel metal has been removed from wastewater.
   - Analytical techniques such as atomic emission spectrometry or mass spectrometry can be used to check the level of nickel pollution in wastewater before and after treatment.

Interpretation of Results

Measured measurement results in the form of the number of grams per minute of nickel attached to the cathode will provide a clear understanding of the efficiency of the electrocoagulation process in the removal of nickel metal from wastewater. The higher the amount of nickel collected at the cathode in a unit of time, the more effective the process will be.

4. Conclusions

This work has found 32 research studies on the application of electrocoagulation for removing nickel from different types of waste water. The studies showed that batch systems using aluminum electrodes with current density ≤ 10 mA/cm^2, electrolysis time < 60 min, initial nickel concentration > 50 mg/L, initial pH in the range of 6 ≤ pH < 11 and distance between electrodes ≥ 1 cm, were the most used. Consequently, the findings of this study will offer valuable insights for researchers and practitioners in enhancing the efficiency of the electrocoagulation process for nickel removal.

Overall, the electrocoagulation process shows great potential in treating nickel in wastewater. However, there are several areas in which more work is needed to make EC technology globally reliable in wastewater treatment. These include:

- Further studies need to be performed to study the effect of other parameters, such as the shape and geometry of electrodes (punched hole and pitch of the holes) and electrode passivation phenomena to reduce the operating cost of the EC process and enhance the efficiency of contaminant removal.

- Additional research is essential to explore the economic feasibility, optimization of electrolytic reactors, and advanced electrode material development.
- Conducting electrocoagulation experiments on a pilot plant scale using real industrial effluent to explore the possibility of using electrocoagulation for treatment of real industrial effluents.
  The combination of electrocoagulation technologies with other treatment processes such as filtration and biological treatment process, presents a holistic approach toward achieving sustainable wastewater treatment processes.

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