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Characterisation of galvanisation effluent using lime-anionic polyacrylamide: A case study from Gauteng, South Africa

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Abstract: Galvanisation, a critical industrial process for rust prevention, generates effluents containing heavy metals and other pollutants, posing environmental and health risks. This study evaluates the effectiveness of a combined lime-anionic polyacrylamide (PAM) treatment to reduce these contaminants from effluent generated by the galvanising industry in Gauteng, South Africa. Effluent samples were collected and analysed for heavy metals (Cd, Cr, Cu, Pb, Zn, Mn, Fe) and physicochemical parameters, including electrical conductivity, chloride, and pH, using standard methods. Untreated effluent exhibited high levels of heavy metals, particularly lead, zinc, manganese, and iron, far exceeding local discharge limits. Post-treatment analysis showed substantial reductions in metal concentrations, achieving compliance with regulatory standards, with pH-adjusted to optimal levels for metal hydroxide precipitation. Additionally, chloride concentrations were reduced from 14,383.24 mg·dm^{-3} to 3,890.40 mg·dm^{-3} and electrical conductivity from 130.50 to 21.10 μS·cm^{-1}. Despite these improvements, the values still exceeded the municipality's discharge limits of 500 mg·dm^{-3} for chloride and 0.1 μS·cm^{-1} for conductivity, indicating residual high ion concentrations. While the lime-PAM treatment effectively improved effluent quality, the results suggest a need for supplementary treatments to achieve full compliance with stringent regulatory standards. Overall, the lime-PAM approach shows potential for reducing heavy metals and physicochemical contaminants reduction in galvanising effluent. However, further optimisation and integration of advanced treatment technologies are recommended to enhance efficacy and ensure environmental compliance.

Keywords: coagulation, coagulation-flocculation, galvanisation industry, heavy metals, industrial effluent

INTRODUCTION

Galvanisation, the process of applying a protective zinc coating to iron or steel to prevent rusting, is an essential industrial procedure that significantly extends the longevity of metal products (Sawalha *et al.*, 2016). The galvanising industry, however, generates substantial volumes of effluent containing various heavy metals, suspended solids, and other contaminants, which pose significant environmental and health risks (Majumdar, Baruah and Dutta, 2007; Berradi *et al.*, 2014). Ensuring the safe disposal or treatment of this effluent is thus a pressing environmental concern.

Effluents released from galvanisation processes often contain hazardous elements such as zinc, lead, chromium, and nickel (Tamimi, Shaheen and Tamimi, 2016). These heavy metals can accumulate in the environment, potentially entering water bodies and soil systems, thereby posing serious risks to aquatic life and human health. Studies have demonstrated the propensity for heavy metals to disrupt biological processes, leading to toxicity in flora and fauna (Briffa, Sinagra and Blundell, 2020; Ding *et al.*, 2022). Consequently, stringent regulations govern the discharge of such effluents, necessitating effective treatment methods to mitigate environmental impact of these pollutants.

In South Africa, the National Water Act (1998) sets strict standards for wastewater discharge, prohibiting the release of effluents containing hazardous substances, like heavy metals, into water bodies unless they meet permissible levels. Local regulations, such as those enforced by the Emfuleni Local Municipality in the Vaal region, introduce additional wastewater discharge guidelines through the Vaal River System Water Quality Management Plan. The Plan establishes specific limits for hazardous pollutants to safeguard water resources (Sibanyon, 2021). These regulations are enforced by both the Department of Water and Sanitation and the local municipality to ensure that industrial wastewater is adequately treated prior to discharge into the Vaal River, a critical water resource in South Africa.

Traditional methods for treating galvanisation effluents, including chemical precipitation, ion exchange, and adsorption, often present limitations to efficiency, cost, and practicality (Velusamy *et al.*, 2021; Ahmed *et al.*, 2022). Lime treatment, a widely used chemical precipitation technique, effectively reduces the solubility of many heavy metals by forming stable precipitates that can be removed via sedimentation or filtration (Chen *et al.*, 2009). However, the process generates considerable volumes of sludge (Dermentzis, Christoforidis and Valsamidou, 2011), requiring additional handling and disposal efforts.

Recently, anionic polyacrylamide (PAM), a synthetic water-soluble polymer, has gained attention for its applications in water and wastewater treatment (Rabiee, Ershad-Langroudi and Jamshidi, 2014). The PAM enhances particle aggregation, promoting the coagulation and flocculation of suspended particles, thereby improving solid-liquid separation. This study leverages the properties of lime alongside anionic PAM to treat galvanisation effluent, hypothesising that their synergistic effects will result in improved contaminant removal efficiency and reduced sludge volumes.

Lime (calcium hydroxide) is a cost-effective and widely available reagent used to adjust pH levels and precipitate heavy metals from industrial wastewater streams (Charazińska, Burszta-Adamiak and Lochyński, 2022). It is particularly effective in converting dissolved metallic ions into insoluble hydroxides. Numerous studies have demonstrated the efficacy of lime in treating various industrial effluents. Chen *et al.* (2018) highlighted the capacity of lime to precipitate metals such as zinc and copper from electroplating wastes while Tadesse *et al.* (2006) and Dermentzis, Christoforidis and Valsamidou (2011) showed that lime treatment could achieve substantial reductions in the concentrations of chromium and nickel in textile wastewater. However, the production of significant sludge volumes remains a persistent drawback, necessitating the exploration of supplementary agents to improve treatment efficiency.

Anionic PAM is extensively studied for its coagulating and flocculating properties, which enhance the removal of suspended solids and associated contaminants from wastewater. Lentz (2015) reviewed the effectiveness of PAM in promoting flocculation, underscoring its advantages in enhancing particle aggregation. Wong *et al.* (2006) demonstrated that PAM significantly improves settling rates and reduces the turbidity in treated effluents in various industrial applications. Li *et al.* (2022) provided evidence of synergistic effects of combined lime and anionic PAM treatments, showing reduced sludge production while maintaining high contaminant removal efficiencies.

The integration of lime with anionic PAM offers a compelling approach for enhanced effluent treatment. By combining the pH adjustment and metal precipitation benefits of lime with the flocculating properties of PAM, the method shows potential for improved overall treatment efficacy. Chaemiso (2019) observed enhanced removal of heavy metals and decreased sludge volumes when lime was used in conjunction with anionic and cationic polymers. Similarly, Kos (2017) reported improved coagulation and sedimentation performance in textile wastewater treatment using lime and anionic PAM, resulting in better effluent quality and reduced sludge volume compared to lime treatment alone.

Building on these theoretical and empirical foundations, the present study aims to characterise galvanisation effluent treated with a combination of lime and anionic PAM, focusing on removal efficiencies of key contaminants, sludge production, and potential environmental impacts of the treated effluent. Limited studies exist on the application of lime-anionic polyacrylamide for producing coagulants to treat wastewater from galvanising industries.

MATERIALS AND METHODS

STUDY AREA

The study took place in a galvanising facility located in Vanderbijlpark City, South Africa, situated at the coordinates 25°42'21" S latitude and 28°15'7" E longitude, as illustrated in Figure 1.

EFFLUENT SAMPLING

In this study, 34 samples were collected between September 2020 and February 2021 to encompass various seasons and operational phases. Composite sampling was performed using clean containers, which were accurately labelled with the date, time, and sampling location (Lemessa *et al.*, 2023). Acid preservatives were added to the samples, which were then stored at 4°C to prevent chemical and biological alterations following ISO 5667-3:2024 guidelines.

HEAVY METAL ANALYSIS

Heavy metals such as Cd, Cr, Cu, Pb, Zn, Mn, and Fe were analysed using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) with a Thermo Scientific iCAP 7000 Plus Series ICP-OES spectrometer (Massachusetts, USA), equipped with an ASX-520 autosampler. The operational parameters for the ICP-OES followed the standard procedure as outlined by Vanini *et al.* (2015). Calibration standards for the elements were utilised to create the calibration curve, with a five-

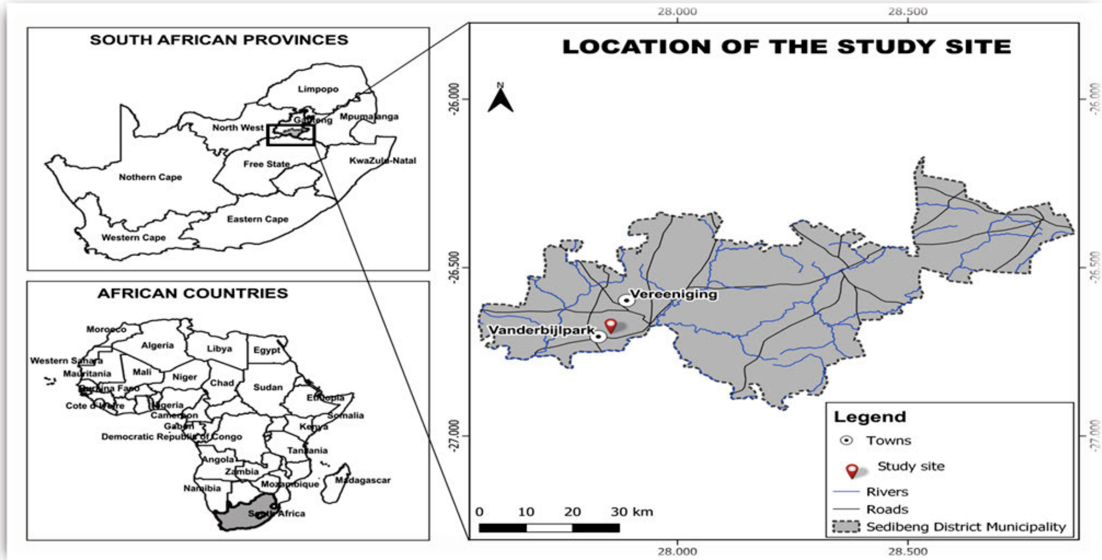

Fig. 1. The location of the study area (Galvanising Industry) in the Vaal region; source: own elaboration

point calibration carried out alongside all samples to verify the sensitivity of ICP-OES. The response factor (R^2) for each heavy metal ranged from 0.9670 to 0.9986. Detection and quantification limits were determined using three and ten times the standard deviation of the blank, respectively, relative to the slope of the regression line. Results from the calibration standards were reported in triplicate.

PHYSICOCHEMICAL ANALYSIS

The effluent quality was evaluated by examining its electrical conductivity (*EC*), chloride (Cl^-) levels, and pH using standard methods. The pH was recorded at 25°C with a Thermo Scientific pH meter, while electrical conductivity was measured with an INOLAB Conductivity meter following the standard procedure by Koetlisi and Muchaonyerwa (2019). Chloride content was determined using the Mohr method, as modified by Belcher, Macdonald and Parry (1957).

COAGULATION-FLOCCULATION

To determine the optimal coagulant dose for raw effluent samples, a series of coagulation-flocculation jar tests were conducted using lime as the primary coagulant and anionic polyacrylamide as a coagulant aid (flocculant). All tests were performed at the natural pH level for the effluent. The experimental setup involved varying the coagulant dose from 5,000 to 15,000 mg·dm^{-3} for both lime and polyacrylamide across three separate runs, with specified mixing durations for each run (Tab. 1).

Following the coagulation-flocculation process, the treated samples were allowed to settle for one hour. After settling, the supernatant was collected and analysed for heavy metal concentrations using ICP-OES to determine the removal efficiency (*RE*%) of the process, as calculated using Equation (1):

$$RE\% = \left(\frac{CUE - CTE}{CUE}\right)100 \qquad (1)$$

where: *CUE* = concentration of untreated effluent, *CTE* = concentration of treated effluent.

STATISTICAL ANALYSIS

Physicochemical data were collected, structured, and analysed using GraphPad Prism v 9.5.1. The measured properties were then compared to the discharge limits established by South Africa and the local municipality. Results were categorised based on whether they exceeded or complied with the acceptable limits. Data analysis included calculations of the mean and standard deviation (mean ±*SD*).

Table 1. Conditions for experimental testing

Series	Run 1 (lime)	Run 2 (polymer)	Run 3 (lime: polymer)	Stirring condition	
	mg·dm^{-3}			time of rapid mixing	time of slow mixing
1	5,000	50	5,000:150	3 min at 300 rpm	15 min at 50 rpm
2	7,500	75	7,500:125	3 min at 300 rpm	15 min at 50 rpm
3	10,000	100	10,000:100	3 min at 300 rpm	15 min at 50 rpm
4	12,500	125	12,500:75	3 min at 300 rpm	15 min at 50 rpm
5	15,000	150	15,000:50	3 min at 300 rpm	15 min at 50 rpm

Source: own elaboration.

RESULTS AND DISCUSSION

HEAVY METALS CHARACTERISATION OF THE GALVANISING EFFLUENT SAMPLE

Table 2 shows the heavy metal composition over a six-month period, compared with the permissible limits established by the Department of Water Affairs and Forestry (DWAF), South Africa, and local municipal effluent discharge standards (DWAF, 1995).

Table 2. Heavy metals characteristics of the galvanising effluent of 34 collected samples

Heavy metal	Range	Average value	South Africa discharge limit	Local discharge limit
	mg·dm^{-3}			
Lead	93.82–309.42	191.86 ±71.84	≤0.05	≤5.0
Copper	0.00–1.46	0.71 ±0.45	≤0.5	≤5.0
Zinc	36.45–112.86	64.73 ±26.12	≤2.0	≤20.0
Manganese	7.40–29.00	17.02 ±6.73	≤0.2	≤20.0
Chromium	2.12–4.72	3.38 ±0.73	≤0.05	≤20.0
Cobalt	0.00–0.14	0.05 ±0.06	≤0.05	≤20.0
Nickel	0.00–1.41	0.95 ±0.40	≤0.1	≤20.0
Iron	224.75–481.82	371.69 ±98.85	≤2.0	≤20.0

Source: own study.

The average concentrations of lead, zinc, manganese, and iron in the effluent are significantly higher than both the South African and local discharge limits. This indicates a severe non-compliance and significant environmental concerns. The average concentrations of copper, nickel, and chromium exceed the South African discharge limit by a considerable margin but remain within the local limits. However, cobalt concentrations fall within both the South African and local discharge limits.

Comparing these values with available studies, it is evident that heavy metal concentrations in galvanising effluent often significantly exceed regulatory limits, especially for elements such as lead, zinc, and iron. Studies generally indicate that treatment processes focusing on reducing these heavy metal concentrations are crucial for ensuring compliance and safeguarding environmental health.

This comparison shows significant exceedances in several heavy metals, highlighting the need for improved effluent treatment processes to meet regulatory standards. The environmental and health risks posed by these exceedances necessitate immediate attention to ensure remediation and compliance.

Studies consistently report high concentrations of lead and zinc in galvanising effluents. Ribeiro *et al.* (2018) found that lead concentrations in untreated galvanising effluents could exceed regulatory limits by as much as 200 times, while zinc levels could surpass limits by up to 50 times. These findings align with the high lead and zinc levels observed in the current analysis. Similarly, high manganese and chromium concentrations in galvanising effluents have been observed by Oyem, Oyem and Usese (2015), who noted values exceeding permissible limits, posing severe risks to aquatic ecosystems. The manganese and chromium levels detected in the current analysis support these findings. The high levels of iron, reaching 317.92 mg·dm^{-3} in the current study, are consistent with Marson *et al.* (2022), who reported that iron concentrations in galvanising effluents far exceeded both local and national discharge limits, necessitating robust treatment solutions. Although the levels of copper (0.71 mg·dm^{-3}) and cobalt (0.07 mg·dm^{-3}) measured in the current study are within local limits, they exceed South African standards. This is consistent with Wakawa, Uzairu, and Balarabe (2008), who demonstrated that copper and cobalt concentrations in industrial effluents often exceed more stringent national standards, highlighting the need for localised regulations that reflect regional industrial practices. The nickel concentration in the effluent remains within both South African and local discharge limits (0.06 mg·dm^{-3}). This is supported by Borbély and Nagy (2009), who observed that nickel levels in galvanising processes are generally controlled more effectively compared to other heavy metals.

The elevated levels of heavy metals observed in the galvanising effluent are due to the use of chemicals such as caustic solutions, 10–16% hydrochloric acid, and 30% zinc ammonium chloride, during the manufacturing process. These chemicals are necessary for surface cleaning and coating (Tchounwou *et al.*, 2012). Given these findings, it is evident that current treatment processes for galvanising effluents are insufficient to reduce the elevated concentrations of several heavy metals. To achieve compliance, it is essential to stablish and enhance treatment methods such as chemical precipitation, ion exchange, and advanced filtration technologies. The public health implications of heavy metal contamination are profound, particularly the neurotoxic effects of lead, which are well-documented and pose significant risks, especially to children (Sharma, Chambial and Shukla, 2015). Ensuring that the effluents meet stringent discharge limits is crucial to protect both human populations and aquatic ecosystems from the adverse effects of these contaminants.

PHYSICOCHEMICAL CHARACTERISATION OF THE GALVANISING EFFLUENT SAMPLE

Physicochemical characteristics of the galvanising effluent are shown in Table 3, detailing parameter ranges, average values, and their comparison with both South African and local discharge limits. The average concentration of chlorides in the effluent (14,383.24 mg·dm^{-3}) is significantly higher than both the South African and the local discharge limits. This suggests that the chloride levels substantially exceed acceptable norms, indicating severe non-compliance and potential risks to water salinity and ecosystem health. The high levels of chloride found in the effluent are attributed to the use of hydrochloric acid in the metal cleaning process before galvanising (Eka *et al.*, 2012). Similar findings of high chloride concentrations in galvanising wastewater were reported in a study by UMMCST (2013). However, at high levels (>230 mg·dm^{-3}), Cl^- in water leads to unpleasant odours and salty taste (DOH, 2018). Additionally, high chloride levels have severe environmental effects, such as corroding metal structures and causing equipment damage in industrial settings.

The measured *EC* far exceeds the South African limit of 1.5 μS·cm^{-1} and local discharge limit of 0.1 μS·cm^{-1}, indicating

Table 3. Analysis of physicochemical characteristics of the galvanising effluent in 34 collected samples

Parameter	Range	Average value	South Africa discharge limit	Local discharge limit
Chloride (mg·dm^3)	8,997–22,470	14,383.24 ±3,890.40	≤1500	≤500.0
Electrical conductivity (µS·cm^{-1})	97.41–165.80	130.50 ±21.10	0.7–1.5	≤0.1
pH	0.53–1.78	1.07±0.31	5.0–9.5	6–10

Source: own study.

a high concentration of dissolved ions and significant non-compliance. A study by Majumdar, Baruah, and Dutta (2007) also reported high *EC* values 104.34–140.36 µS·cm^{-1} in galvanising effluent. The increased *EC* levels in the effluent is due to contaminants such as Na^+, Ca^{2+}, Mg^{2+}, Cl^- and other metal salts introduced through the use of NaOH and $Ca(OH)_2$ in the manufacturing processes (Berradi *et al.*, 2014). While high *EC* values in water may not be hazardous to human health (Rahmanian *et al.*, 2015), they result in corrosion of industrial equipment and plumbing systems (Tudararo-Aherobo and Egieya, 2023). The effluent pH is highly acidic (1.07 on average), which falls far below both the South African (5.0–9.5) and local discharge limits (6–10). Such low pH levels can have severe impacts on aquatic life and industrial infrastructure. This study's results align with El Diwani *et al.* (2022) research, indicating a pH of 1–3 for removing fluoride pollutants from industrial wastewater. Additionally, Sawalha *et al.* (2016) reported a pH of 1.4 in their study on wastewater characterisation and treatment in Palestine's galvanising industry.

The high Cl^- levels, *EC*, and extremely low pH indicate potentially severe environmental consequences, including toxicity to aquatic organisms, alteration to water chemistry, and damage to aquatic habitats. Elevated chloride levels and low pH can influence water potability and its agricultural use, affecting human health and agricultural productivity.

COAGULATION-FLOCCULATION TREATMENT

Heavy metals analysis

The data (Fig. 2) illustrates significant variability of metal coagulation with pH changes. Lead recovery shows a positive trend with rising pH levels. At low pH of 1.2, no recovery is observed, but the recovery percentage significantly increases between pH 3.2 and 9.2, reaching full recovery at pH 9.2. Studies indicate that Pb can form insoluble hydroxides and carbonates at higher pH levels, which precipitate out of solution. This explains the higher recovery rates observed at higher pH (Lin *et al.*, 2016). Similarly, Zn recovery improves with increasing pH. According to the Emfuleni Local Municipality regulations (2004), the permissible limits of metals in effluents are as follows: Pb ≤ 5 mg·dm^{-3}, Mn ≤ 20.0 mg·dm^{-3}, Zn ≤ 20.0 mg·dm^{-3}, and Fe ≤ 20.0 mg·dm^{-3}.

The data demonstrates a noticeable increase recovery starting from pH 3.2, climbing to almost complete recovery at pH 7.2 and complete by pH 9.2. Zinc is known to precipitate as

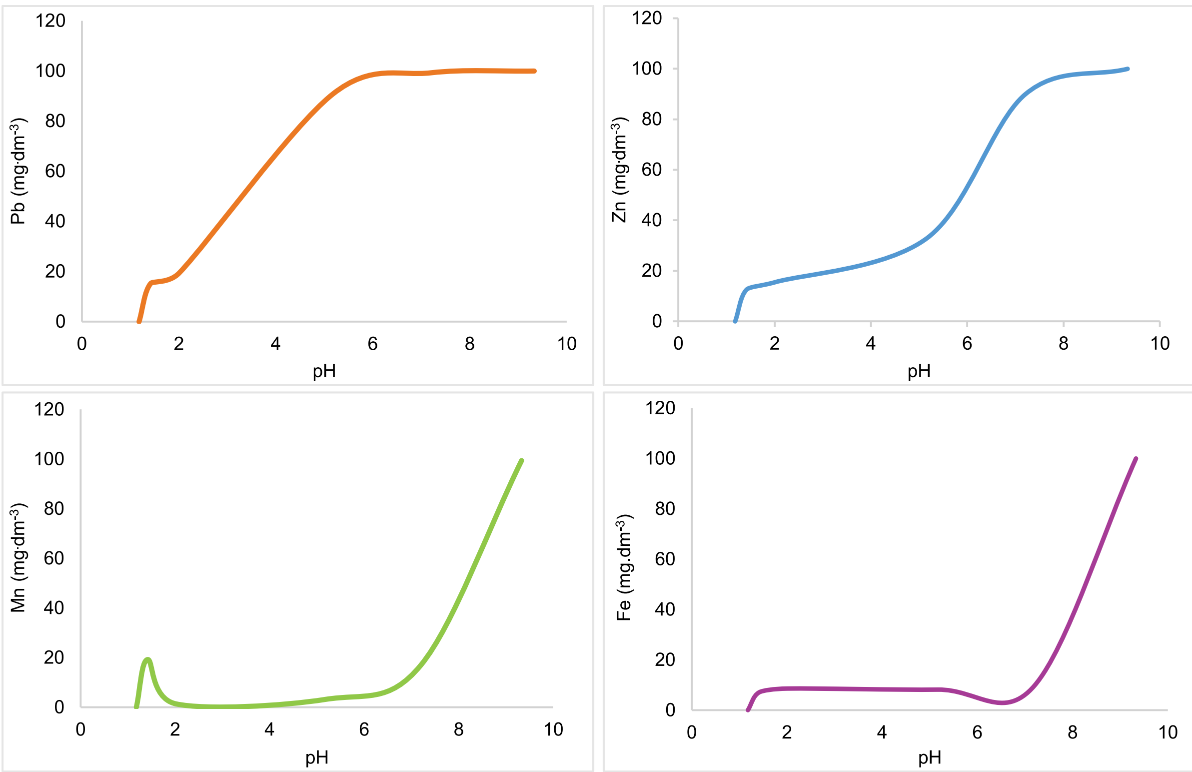

Fig. 2. Effect of pH on the recovery/removal of heavy metals by lime-anionic acrylamide; source: own study

Zn hydroxide as pH increases, supporting the higher recovery rates observed at higher pH (Lim *et al.*, 2021). Manganese recovery shows a drop at pH 3.2 but improves significantly at pH 9.2, suggesting its solubility decreases sharply at higher pH levels. The solubility of Mn decreases sharply above pH 8.0, due to the formation of $Mn(OH)_2$, which precipitates (Hem, 1963). Iron shows low recovery at lower pH and a substantial increase only at pH 9.2, suggesting that iron coagulation efficiency is the highest in alkaline conditions. The formation of insoluble $Fe(OH)_3$ increases with higher pH, leading to increased coagulation efficiency (Lim *et al.*, 2021). The degree of metal coagulation is highly pH-dependent: low pH (1.2–3.2) supports poor recovery for all metals, indicating solubility in acidic conditions, medium pH (5.2–7.2) – significant improvements in Pb and Zn recovery, while Fe also starts showing better recovery, high pH (9.2) – almost complete recovery for all metals, confirming that alkaline conditions promote the coagulation of these metals. The mechanism of heavy metal removal by chemical precipitation is presented in Equation (2):

$$Metal^{\,n+} + \mathrm{Ca(OH)_2} \rightarrow Metal\,\mathrm{(OH)}_n \downarrow \mathrm{Ca^{2+}} \qquad (2)$$

Potential of hydrogen (pH) analysis

The data in Figure 3 illustrates the pH levels of untreated and treated galvanising effluent sampled across various days from September 2020 to February 2021. Throughout this period, the untreated effluent consistently exhibited acidic pH levels. In September 2020, pH values for the untreated effluent fluctuated between 0.92 and 1.78, reflecting highly acidic conditions. In October 2020, there was a slight increase with pH levels ranging from 1.02 to 1.52. A significant drop was observed in November 2020, with pH values between 0.64 and 0.67. From January to February 2021, the pH remained low, ranging from 0.53 to 1.19. Before treatment, the pH levels fell outside the acceptable range for discharging wastewater into water resources. The range is set by the National Water Act (1998) between 5.5 and 9.5.

After the application of the treatment process, the pH levels of the effluent shifted significantly towards neutrality or alkalinity. In September 2020, treated effluent pH ranged between 7.06 and 9.12, indicating successful neutralisation or alkalisation. In October 2020, the pH levels varied slightly, fluctuating from 5.12 to 8.32. November 2020 saw pH levels maintained between 5.9 and 8.79, demonstrating consistent treatment results. From January to February 2021, pH values showed stability, ranging

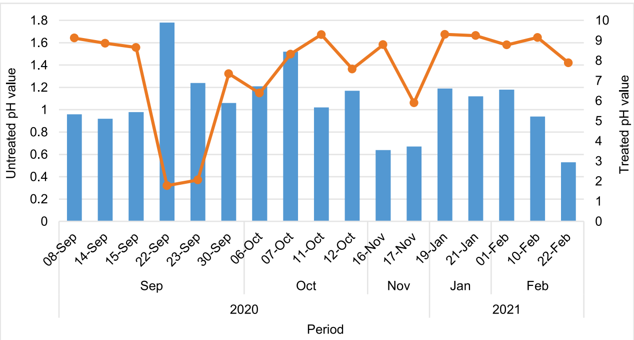

Fig. 3. Potential of hydrogen (pH) variation in galvanising effluent from September 2020 to February 2021; source: own study

from 7.89 to 9.61 and maintaining effective neutralisation. However, despite the addition of lime leading to pH values generally within the local municipality's discharge limit of 6.0–10.0, one reading of 1.78 was recorded below this limit. The post-treatment pH levels remain within the permissible range for discharging wastewater into water resources. This is set by the National Water Act (2013) between 5.5 and 9.5. This increase in pH with higher lime concentrations can be attributed to the release of OH^- ions into the solution. According to Aniyikaiye *et al.* (2019), low pH levels in galvanising effluent can enhance the solubility of heavy metals, resulting in the release of metal cations into the environment instead of their absorption by sediment. Hence, controlling acidic effluent is crucial to prevent the corrosion of metal pipes and plumbing systems (Tranvik, 2021).

Electrical conductivity analysis

The data presented in in Table 4 highlights the levels of *EC*, calcium, sodium, and magnesium in both untreated and treated effluent.

Table 4. Recovery and concentration of galvanising effluent before and after galvanising effluent treatment

Pollutant	Untreated (average)	Treated (average)	Removal (%)
Ca^{2+} (mg·dm^{-3})	464	2860	–516.38
Mg^{2+} (mg·dm^{-3})	35	29	17.14
Na^{+} (mg·dm^{-3})	109	43	60.55
EC (µS·cm^{-1})	130.50	28.64	78.05

Explanations: *EC* = electrical conductivity.
Source: own study.

These levels are compared to the standard limits set by the local municipality as follows *EC* (Tab. 3), calcium (not available), sodium (1000 mg·dm^{-3}), and magnesium (not available) (CoCT, 2013). The concentration of Ca^{2+} in the untreated effluent was 464 mg·dm^{-3}, while in the treated effluent it increased to 2,860 mg·dm^{-3} as demonstrated in Table 4. This rise is attributed to the addition of lime during the treatment process, which then releases calcium ions and hydroxide ions into the effluent. The $Ca(OH)_2$ can precipitate magnesium as $Mg(OH)_2$, typically achieving removal efficiencies ranging from 50–85%. Sodium is typically more challenging to remove using $Ca(OH)_2$ treatment due to its high solubility and the absence of participating precipitation reactions. A 71.43% removal efficiency significantly exceeds typical expectations for sodium removal with $Ca(OH)_2$ alone. This suggests that other factors or additional treatments might be contributing to the observed removal efficiency.

The data indicates that $Ca(OH)_2$ treatment is highly effective for Mg^{2+} removal (66.67%). However, the observed removal efficiency for Na^+ (71.43%) is notably higher than typically reported for $Ca(OH)_2$ treatment alone, suggesting either additional treatment steps or specific operating conditions enhancing sodium removal.

The *EC* values changed from a mean of 130.50 µS·cm^{-1} (untreated) to 28.64 µS·cm^{-1} (treated), achieving the removal efficiency of 78.5%. However, despite this reduction, the EC levels still exceed the local municipality's allowable discharge limit of ≤0.1 μS·cm^{-1}. The findings of this study align with those of Arroub and Harfi (2019), who found a removal efficiency of 72.85% in the treatment of hot dip galvanising liquid effluents. As a result, lime is used to coagulate the ions and molecules, which leads to a decrease in conductivity (Hasna *et al.*, 2020).

Chloride analysis

The data presented in Figure 4 highlights the levels of *EC* and Cl^- in both untreated and treated effluent. These levels are compared to the standard limits set by the local municipality.

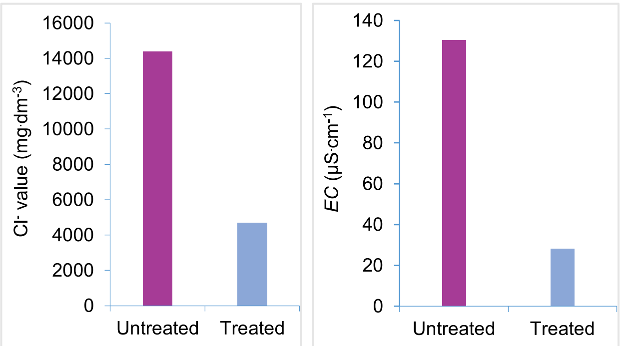

Fig. 4. Chloride (Cl^-) and electrical conductivity (*EC*) values of untreated and treated effluents results obtained using the lime-anionic acrylamide; source: own study

The untreated effluent shows an extremely high chloride concentration and *EC* of 14,383.24 mg·dm^{-3} and 130.50 μS·cm^{-1}, respectively, which are far above the acceptable municipality limit. The elevated *EC* value suggests a high concentration of dissolved ions. After treatment with lime-anionic acrylamide, the conductivity and chloride concentration significantly decreases to 3,890.40 mg·dm^{-3} (resulting in a 67.4% Cl^-, removal efficiency) and 21.10 μS·cm^{-1}, respectively. Lime addition to the effluent results in the formation of calcium chloride as stipulated in Equation (3).

$$\mathrm{Ca(OH)_{2(aq)}} + \mathrm{2HCl_{(aq)}} \rightarrow \mathrm{CaCl_{2(aq)}} + \mathrm{2H_2O_{(l)}} \qquad (3)$$

Calcium chloride is both a pollutant to be removed and a coagulant. The formation of calcium chloride acts as a secondary coagulate, which helps to destabilise charged particles and colloids present in the effluent (Arbete, Vogel and Styckares, 2015). Despite these removal processes, a considerable amount of residual chloride remains in the effluent.

The treatment using lime-anionic acrylamide has noticeably reduced both the *EC* and Cl^- levels in the effluent. The reductions are substantial when comparing untreated and treated effluent values. Despite the improvements, the post-treatment values for both parameters (21.10 μS·cm^{-1} for conductivity and 3,890.40 mg·dm^{-3} for chloride) do not meet the local municipality limit of 500. The study reported lower efficiency in removing Cl^- compared to previous research by Saritha *et al.* (2017) who achieved a 78.57% Cl^- removal efficiency using sago in their analysis and optimisation study of the coagulation and flocculation process. Similarly, Stevens and Batlokwa (2018) reported a significant Cl^- removal rate of 80.70% ±2.01% from real wastewater samples through absorption using eggshells.

CONCLUSIONS

This study explored the effectiveness of a lime-anionic acrylamide treatment method in reducing contaminants in effluent from a galvanisation process. The analysis focused on the removal efficiencies of key heavy metals and physicochemical parameters, comparing untreated and treated effluent against local and national discharge limits.

The lime-anionic acrylamide treatment method demonstrates significant potential for improving the quality of effluent from the galvanisation process by substantially reducing heavy metal concentrations and neutralising pH. Nevertheless, the residual levels of certain contaminants, specifically chloride (Cl^-) and electrical conductivity (Cl^-), indicate that additional treatment measures are needed to meet regulatory standards. Integrating more advanced purification techniques, such as reverse osmosis or further chemical treatments, could help achieve compliant discharge limits.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

REFERENCES

Ahmed, M. *et al.* (2022) "Recent developments in hazardous pollutants removal from wastewater and water reuse within a circular economy," *npj Clean Water*, 5(1), 12. Available at: https://doi.org/10.1038/s41545-022-00154-5.

Aniyikaiye, T.E. *et al.* (2019) "Physico-chemical analysis of wastewater discharge from selected paint industries in Lagos, Nigeria," *International Journal of Environmental Research and Public Health*, 16(7), 1235. Available at: https://doi.org/10.3390/ijerph16071235.

Arroub, H. and El Harfi, A. (2019) "Synthesis, modification by epichlorohydrin and characterization of a natural polyelectrolyte polymer and its application in the treatment of hot dip galvanizing water by coagulation/flocculation," *Journal of Applied Science and Environmental Studies*, 2(2), pp. 77–88. Available at: https://revues.imist.ma/index.php/JASES/article/view/16711/9485 (Accessed: June 3, 2024).

Belcher, R., Macdonald, A.M.G. and Parry, E. (1957) "On Mohr's method for the determination of chlorides," *Analytica Chimica Acta*, 16(C), pp. 524–529. Available at: https://doi.org/10.1016/S0003-2670(00)89979-1.

Berradi, M. *et al.* (2014) "Optimization of the coagulation/flocculation process for the treatment of industrial wastewater from the hot dip galvanizing of steel," *Journal of Materials and Environmental Science*, 5(2), pp. 360–365. Available at: https://www.jmaterenvironsci.com/Document/vol5/vol5_N2/42-JMES-486-2013-Berradi.pdf (Accessed: Feburary 22, 2024).

Borbély, G. and Nagy, E. (2009) "Removal of zinc and nickel ions by complexation-membrane filtration process from industrial wastewater," *Desalination*, 240(1–3), pp. 218–226. Available at: https://doi.org/10.1016/j.desal.2007.11.073.

Briffa, J., Sinagra, E. and Blundell, R. (2020) "Heavy metal pollution in the environment and their toxicological effects on humans," *Heliyon*, 6 (9). Available at: https://doi.org/10.1016/j.heliyon.2020.e04691.

Chaemiso, T.D. (2019) "Removal methods of heavy metals from laboratory wastewater," *Journal of Natural Sciences Research*, 9(2), pp. 36–42. Available at: https://doi.org/10.7176/jnsr/9-2-04.

Charazińska, S., Burszta-Adamiak, E. and Lochyński, P. (2022) "The efficiency of removing heavy metal ions from industrial electropolishing wastewater using natural materials," *Scientific Reports*, 12(1), 17766. Available at: https://doi.org/10.1038/s41598-022-22466-9.

Chen, Q. *et al.* (2009) "Precipitation of heavy metals from wastewater using simulated flue gas: Sequent additions of fly ash, lime and carbon dioxide," *Water Research*, 43(10), pp. 2605–2614. Available at: https://doi.org/10.1016/j.watres.2009.03.007.

Chen, Q. *et al.* (2018) "Comparison of heavy metal removals from aqueous solutions by chemical precipitation and characteristics of precipitates," *Journal of Water Process Engineering*, 26, pp. 289–300. Available at: https://doi.org/10.1016/j.jwpe.2018.11.003.

CoCT (2013) *Wastewater and Industrial Effluent By-Law*. Available at: https://resource.capetown.gov.za/documentcentre/Documents/Bylaws%20and%20policies/Wastewater%20and%20Industrial%20Effluent%20By-law%202013.pdf (Accessed: April 13, 2023).

Dermentzis, K., Christoforidis, A. and Valsamidou, E. (2011) "Removal of nickel, copper, zinc and chromium from synthetic and industrial wastewater by electrocoagulation," *International Journal of Environmental Sciences*, 5(1), pp. 21–34. Available at: http://www.theaspd.com/resources/ijes-2019-3.pdf (Accessed: April 13, 2023).

Ding, C. *et al.* (2022) "Biological toxicity of heavy metal(loid)s in natural environments: From microbes to humans," *Frontiers in Environmental Science*, 10, 920957. Available at: https://doi.org/10.3389/fenvs.2022.920957.

DOH (2018) *Color, taste and odor problems in drinking water: Fact sheet*. Washington State Department of Health. Available at: https://doh.wa.gov/sites/default/files/legacy/Documents/Pubs/331-286.pdf (Accessed: January 25, 2024).

DWAF (1995) *Procedures to assess effluent discharge impacts*. Pretoria: Department of Water Affairs and Forestry. Available at: https://www.wrc.org.za/wp-content/uploads/mdocs/TT%2064-94.pdf (Accessed: November 11, 2023).

Eka, N. *et al.* (2012) "Validation and quantitative analysis of cadmium and lead in snake fruit by flame atomic absorption spectrophotometry," *International Food Research Journal*, 19(3), pp. 937–940. Available at: https://www.cabidigitallibrary.org/doi/pdf/10.5555/20133248968 (Accessed: June 7, 2024).

El Diwani, G. *et al.* (2022) "Fluoride pollutants removal from industrial wastewater," *Bulletin of the National Research Centre*, 46(1), 143. Available at: https://doi.org/10.1186/s42269-022-00833-w.

Emfuleni Local Municipality (2004) *Water and Sanitation By-law. Provincial Gazette Extraordinary*, Vol. 10, No. 183, 21 May. Pretoria: Province of Gauteng, pp. 1–55.

Hasna, M. *et al.* (2020) "Study of coagulation process with lime in treatment of landfill leachate from Fkih Ben Salah City (Morocco)," *Journal of Geoscience and Environment Protection*, 8(9), pp. 197–211. Available at: https://doi.org/10.4236/gep.2020.89012.

Hem, J. (1963) "Chemical equilibria and rates of manganese oxidation – Chemistry of manganese in natural water," *US Geological Survey Water-Supply Paper*, 1667-A. Available at: https://pubs.usgs.gov/wsp/1667a/report.pdf (Accessed: May 8, 2024).

ISO 5667-3:2024 *Water quality – Sampling. Part 3: Preservation and handling of water samples*. Geneva: International Organization for Standardization.

Kerdachi, D. (2002) "The review of industrial effluent tariff structures in South Africa and guidelines on the formulation of an equitable effluent tariff structure. Report to the Water Research Commission," *WRC Report*, 854/1/02. Available at: https://www.wrc.org.za/wp-content/uploads/mdocs/854-1-02.pdf (Accessed: December 15, 2023).

Koetlisi, K.A. and Muchaonyerwa, P. (2019) "Sorption of selected heavy metals with different relative concentrations in industrial effluent on biochar from human faecal products and pine-bark,", *Materials*, 12(11), 1768. Available at: https://doi.org/10.3390/ma12111768.

Kos, L. (2017) "Effect of using coagulants on sedimentation sludge properties and quality of textile wastewater," *Fibres and Textiles in Eastern Europe*, 25(1), pp. 126–130. Available at: https://doi.org/10.5604/12303666.1227893.

Lemessa, F. *et al.* (2023) "Assessment of the impact of industrial wastewater on the water quality of rivers around the Bole Lemi Industrial Park (BLIP), Ethiopia," *Sustainability*, 15(5), 4290. Available at: https://doi.org/10.3390/su15054290.

Lentz, R.D. (2015) "Polyacrylamide and biopolymer effects on flocculation, aggregate stability, and water seepage in a silt loam," *Geoderma*, 241–242, pp. 289–294. Available at: https://doi.org/10.1016/j.geoderma.2014.11.019.

Li, L. *et al.* (2022) "Understanding the synergistic mechanism of PAM-$FeCl_3$ for improved sludge dewaterability," *Journal of Environmental Management*, 301(8), 113926. Available at: https://doi.org/10.1016/j.jenvman.2021.113926.

Lim, S.S. *et al.* (2021) "Zinc removal and recovery from industrial wastewater with a microbial fuel cell: Experimental investigation and theoretical prediction," *Science of the Total Environment*, 776 (1), 145934. Available at: https://doi.org/10.1016/j.scitotenv.2021.145934.

Lin, Q.Q. *et al.* (2016) "Separation of manganese from calcium and magnesium in sulfate solutions via carbonate precipitation," *Transactions of Nonferrous Metals Society of China*, 26(4), pp. 1118–1125. Available at: https://doi.org/10. 1016/S1003-6326(16)64210-3.

Majumdar, J., Baruah, B.K. and Dutta, K. (2007) "Evaluation of LC50 of galvanizing industry effluent," *Journal of Industrial Pollution Control*, 23(1), pp. 131–134. Available at: https://www.icontrolpollution.com/articles/evaluation-of-lc50-of-galvanizing-industry-effluent-.pdf (Accessed: October 23, 2023).

Marson, E.O. *et al.* (2022) "Effect of iron complex source on MWWTP effluent treatment by solar photo-Fenton: Micropollutant degradation, toxicity removal and operating costs," *Molecules*, 27(17), 5521. Available at: https://doi.org/10.3390/molecules27175521.

National Water Act (1998) "National Water Act 36 of 1998," *Government Gazette*, No. 19182, *Notice*, No. 1091. Available at: https://cer.org.za/wp-content/uploads/2010/05/General-Authorisations-2009.pdf (Accessed: August 10, 2023).

National Water Act (2013) "National Water Act 36 of 1998. Revision of General Authorisations in terms of section 39 of The National Water Act, 1998 (Act No. 36 of 1998) (The Act)," *Government Gazette*, No. 36820, *Notice*, No. 665. Available at: https://cer.org.za/wp-content/uploads/2014/02/Revision-of-General-Authorisations-2013.pdf (Accessed: January 15, 2024).

Oyem, H.H., Oyem, I.M. and Usese, A.I. (2015) "Iron, manganese, cadmium, chromium, zinc and arsenic groundwater contents of Agbor and Owa communities of Nigeria," *SpringerPlus*, 4(1), 104. Available at: https://doi.org/10.1186/s40064-015-0867-0.

Rabiee, A., Ershad-Langroudi, A. and Jamshidi, H. (2014) "Polyacrylamide-based polyampholytes and their applications," *Reviews in Chemical Engineering*, 30(5), pp. 501–519. Available at: https://doi.org/10.1515/revce-2014-0004.

Rahmanian, N. *et al.* (2015) "Analysis of physiochemical parameters to evaluate the drinking water quality in the state of perak, Malaysia," *Journal of Chemistry*, 2015, 16125. Available at: https://doi.org/10.1155/2015/716125.

Ribeiro, C. *et al.* (2018) "A comprehensive evaluation of heavy metals removal from battery industry wastewaters by applying bio-residue, mineral and commercial adsorbent materials," *Journal of Materials Science*, 53(11), pp. 7976–7995. Available at: https://doi.org/10.1007/s10853-018-2150-6.

Saritha, V. *et al.* (2017) "Analysis and optimization of coagulation and flocculation process," *Applied Water Science*, 7(1), pp. 451–460. Available at: https://doi.org/10.1007/s13201-014-0262-y.

Sawalha, H. *et al.* (2016) "Characterization and treatment of wastewater from galvanization industry in Palestine," *International Journal of Environmental & Water*, 5(3), pp. 37–44. Available at: https://www.researchgate.net/publication/321391481 (Accessed: May 11, 2023).

Tamimi, I., Shaheen M. and Tamimi, Z. (2016) *Heavy metal – Wastewater treatment from galvanization industry using nanoadsorbent*. BSc. Thesis. Hebron Palestine Polytechnic University. Available at: https://scholar.ppu.edu/bitstream/handle/123456789/6304/Heavy%20metal-%20Wastewater%20Treatment%20from%20Galvanization%20Industry%20Using%20Nanoadsorbent.pdf?sequence=2&isAllowed=y (Accessed: November 8, 2023).

Sharma, P., Chambial, S. and Shukla, K.K. (2015) "Lead and neurotoxicity," *Indian Journal of Clinical Biochemistry*, 30(1), pp. 1–2. Available at: https://doi.org/10.1007/s12291-015-0480-6.

Sibanyon, J.B. (2021) *Final Report of the Gauteng Provincial Inquiry Into the Sewage Problem of the Vaal River*. Johannesburg: South African Human Rights Commission.

Stevens, M. and Batlokwa, B. (2018) "Removal of excess toxic chloride and fluoride anions from wastewater employing eggshells waste remains," *International Journal of Advanced Engineering Research and Science*, 5(9), pp. 79–80. Available at: https://doi.org/10.22161/ijaers.5.9.9.

Tadesse, I. *et al.* (2006) "Lime enhanced chromium removal in advanced integrated wastewater pond system," *Bioresource Technology*, 97(4), pp. 529–534. Available at: https://doi.org/10.1016/j.biortech.2005.04.028.

Tchounwou, P.B. *et al.* (2012) "Heavy metal toxicity and the environment," in A. Luch (ed.) *Molecular, clinical and environmental toxicology. Experientia Supplementum*, 101, pp. 133–164. Available at: https://doi.org/10.1007/978-3-7643-8340-4_6.

Tranvik, L.J. (2021) "Acidification of inland waters: This article belongs to Ambio's 50th Anniversary Collection. Theme: Acidification," *Ambio*, 50(2), pp. 261–265. Available at: https://doi.org/10.1007/s13280-020-01441-6.

Tudararo-Aherobo, L.E. and Egieya, A.J. (2023) "Physicochemical and microbial characterization of treated and untreated produced water," *Journal of Advances in Microbiology*, 23(4), pp. 38–49. Available at: https://doi.org/10.9734/jamb/2023/v23i4719.

UMMCST (2013) *The effects of chloride from waste water on the environment*. Morris: University of Minnesota, Center for Small Towns. Available at: https://environment.umn.edu/wp-content/uploads/2016/03/MS-0008-12-Final-Addendum.pdf (Accessed: May 20, 2023).

Vanini, G. *et al.* (2015) "Multivariate optimisation of ICP OES instrumental parameters for Pb/Ba/Sb measurement in gunshot residues," *Microchemical Journal*, 120, pp. 58–63. Available at: https://doi.org/10.1016/j.microc.2015.01.003.

Velusamy, S. *et al.* (2021) "A review on heavy metal ions and containing dyes removal through graphene oxide-based adsorption strategies for textile wastewater treatment," *Chemical Record*, 21(7), pp. 1570–1610. Available at: https://doi.org/10.1002/tcr.202000153.

Vogel, K. (2015) "Styckares arbete – Knivskarpt om hållbarhet [Meat cutting work and sustainability]," Doktorsavhandling, 7. Stockholm: Kungliga Tekniska högskolan Vetenskap och konst. Available at: https://www.researchgate.net/publication/282132425_Styckares_arbete_-_knivskarpt_om_hallbarhet (Accessed: March 11, 2024).

Wakawa, R.J., Uzairu, A. and Balarabe, M.L. (2008) "Impact assessment of effluent discharge on physico-chemical parameters and some heavy metal concentrations in surface water of River Challawa Kano, Nigeria," *African Journal of Pure and Applied Chemistry*, 2 (10), pp. 100–106. Available at: https://academicjournals.org/article/article1379424578_Wakawa%20et%20al.pdf (Accessed: December 12, 2023).

Wong, S.S. *et al.* (2006) "Treatment of pulp and paper mill wastewater by polyacrylamide (PAM) in polymer induced flocculation," *Journal of Hazardous Materials*, 135(1–3), pp. 378–388. Available at: https://doi.org/10.1016/j.jhazmat.2005.11.076.