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Efficiency of phosphate concentration reduction in laundry wastewater using the electrocoagulation method

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ABSTRACT

Laundry wastewater contains high levels of phosphates derived from detergent additives, such as sodium tripolyphosphate (STPP), which can trigger eutrophication and degrade water quality if discharged directly into water bodies without treatment. This study aimed to evaluate the efficiency of the electrocoagulation method in reducing phosphate concentrations in laundry wastewater and to assess its potential as a practical and environmentally friendly solution for wastewater management. The electrocoagulation process utilized aluminum electrodes with varying voltages (10, 20, and 30 volts) and contact times (30, 60, and 90 minutes). The results showed that the highest efficiency was achieved at 30 volts and a contact time of 90 minutes, with a phosphate concentration reduction of 96.61%, from 0.277 mg/L to 0.009 mg/L. These findings indicate that increasing voltage and contact time accelerates floc formation and enhances phosphate precipitation efficiency. Thus, electrocoagulation proved to be an efficient and environmentally friendly alternative to conventional coagulation, as it requires no additional chemicals and produces less sludge.

1. Introduction

The laundry business is a practical solution for communities to meet their clothing washing needs, especially for those with limited time or equipment. However, despite these benefits, the laundry industry can negatively impact on the environment if untreated wastewater is discharged directly into water bodies [1]. Large quantities of laundry wastewater can pollute water bodies, adversely affecting human health and ecosystem balance. The contaminants in this wastewater have the potential to degrade environmental quality and accelerate the depletion of water resources [2].

The washing process involves mixing water with detergents containing surfactants as cleaning agents, resulting in wastewater with various pollutants, including Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Total Suspended Solids (TSS) [3], high phosphate levels [4], and parameters such as pH, temperature, and salinity [5].

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Table 1
Domestic wastewater effluent quality standards per regulation No. P.68 of 2016, Minister of Environment, Republic of Indonesia.

No.	Parameter	Units	Maximum level
1.	pH	-	6-9
2.	BOD	mg/L	30
3.	COD	mg/L	100
4.	TSS	mg/L	30

Table 1 presents the domestic wastewater effluent quality standards as per the Regulation of the Minister of Environment of the Republic of Indonesia No. P.68 of 2016, which serves as a reference to determine whether washing effluent meets the maximum permissible limits [6].

This research focuses on phosphate, a major pollutant in laundry wastewater derived from detergent additives such as Sodium Tripolyphosphate (STPP). Phosphates are used in detergents to bind calcium and magnesium ions, improving clean efficiency by enhancing the performance of surfactants and enzymes [7]. However, phosphates are often discharged into surface water with wastewater, significantly contributing to water pollution. As phosphates are insoluble, they tend to be absorbed into the soil and transported to water bodies through soil erosion [8]. High phosphate levels can trigger eutrophication, causing algal blooms that deplete dissolved oxygen, harm aquatic organisms, disrupt ecosystems, and degrade water quality, ultimately posing serious risks to environmental and human health [9], [10].

To control water pollution, Government Regulation of the Republic of Indonesia No. 22 of 2021 establishes maximum phosphate concentration limits in water bodies based on their class: 0.2 mg/L for Classes 1 and 2, 1.0 mg/L for Class 3, and 4 mg/L for Class 4. These standards aim to maintain water quality, prevent eutrophication, and protect aquatic ecosystems from the adverse effects of phosphate-containing waste. This regulation also serves as a legal basis for businesses and communities to manage wastewater responsibly to avoid environmental pollution [11]. Various wastewater treatment technologies are used for laundry wastewater, including coagulation-flocculation, biological treatment systems, advanced oxidation processes (AOPs), and conventional filtration [12], [13], [14]. While coagulation-flocculation is simple and effective for suspended particles, it produces large amounts of sludge and is less effective for dissolved contaminants. Biological systems are effective for biodegradable organic compounds but are unsuitable for toxic or non-biodegradable compounds and require time and strict microbiological control. Advanced oxidation processes (AOPs) can oxidize complex organic compounds but are expensive, produce unidentified by-products, and require proper pretreatment [15], [16]. Therefore, selecting an alternative laundry wastewater treatment method that is effective, environmentally friendly, and sustainable is critical. Electrocoagulation is considered a promising method for reducing pollution without causing further environmental impacts and minimizing the use of chemical additives [17], [18]. This method generates coagulants directly from metal electrodes during the process, eliminating the need for external chemical additions and producing significantly less sludge compared to conventional coagulation [19], [20].

Electrocoagulation is a wastewater treatment process that uses electrochemical principles, where coagulants and metal hydroxides are generated in-situ through the dissolution of metal anodes, such as aluminum or iron. These coagulants destabilize and aggregate suspended, dissolved, and dispersed contaminants. Compared to conventional chemical coagulation, electrocoagulation is more effective at removing contaminants without requiring additional chemical reagents and produces less sludge [21], [22]. In the electrocoagulation process, coagulants form in-situ through dissolution at the metal anode, producing metal ions and hydroxide formation at the cathode. These ions undergo hydrolysis reactions to form insoluble (oxy)hydroxides that act as flocs, adsorbing and trapping pollutants through mechanisms such as adsorption, coprecipitation, and charge neutralization, facilitating pollutant separation from water via sedimentation or flotation [23].

Although many studies have explored electrocoagulation for industrial wastewater treatment, most focus on pollutants such as BOD, COD, TSS, and detergents. However, phosphate in laundry wastewater is a primary cause of aquatic eutrophication, adversely affecting water quality. Specific studies on the effectiveness of electrocoagulation in reducing phosphate concentrations, particularly in domestic laundry wastewater, remain limited. The rapid growth of laundry businesses around Universitas Muhammadiyah Surakarta underscores the urgency of sustainable wastewater management, as many of these businesses lack efficient waste treatment systems. Therefore, this study aims to assess the effectiveness of electrocoagulation in reducing phosphate concentrations in laundry wastewater. Additionally, it evaluates the potential of electrocoagulation as a practical and environmentally friendly solution that laundry businesses can adopt to manage wastewater more responsibly.

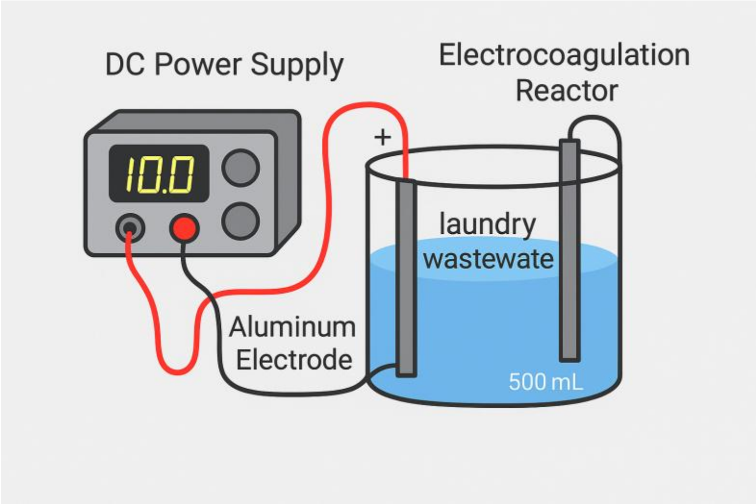

Fig. 1. Electrocoagulation reactor design.

Table 2
Initial parameters

No	Parameter	Testing level before electrocoagulation (mg/L)
1	Phosphate	0.318

Table 3
Decrease in phosphate concentration after electrocoagulation

Voltage (Volt)	Time (minute)	Absorbance	Concentration (mg/L)	Efficiency (%)
Initial parameter	0	0.318	0.277	0
10	30	0.157	0.116	58.04
10	60	0.151	0.110	60.20
10	90	0.149	0.108	60.92
20	30	0.105	0.064	76.79
20	60	0.096	0.055	80.03
20	90	0.092	0.051	81.47
30	30	0.056	0.015	94.45
30	60	0.052	0.011	95.89
30	90	0.05	0.009	96.61

2. Material and method

2.1. Material

The research was conducted at the Chemical Engineering Laboratory of Universitas Muhammadiyah Surakarta, using laundry liquid wastewater samples taken from Green Laundry located at Jalan Tanuragan 2 No. 13, Nilasari, Gonilan, Kartasura District, Sukoharjo Regency, Central Java. Phosphate testing used sulfuric acid solution (H_2SO_4), ascorbic acid solution ($C_6H_8O_6$), potassium antimonyl tartrate solution ($K(SbO)C_4H_6O_6.{}^1/_2H2O$), ammonium molybdate solution ($(NH_4)_6Mo7O_{24}$. $4H_2O$) and mixed solution. The equipment used is a reactor using a 500 ml beaker glass, 5x15 cm aluminum electrode pair and DC power supply.

2.2. Method

Fig. 1 shows the reactor design for this research. Before electrocoagulation, the initial phosphate concentration was measured. In the initial stage, pour 500 mL of the laundry wastewater sample into a 500 mL beaker. Submerge a pair of aluminum electrodes, each with an area of 5 x 15 cm, in parallel. Connect the electrodes to a DC power supply, designating one as the anode and the other as the cathode. Turn on the power supply, adjust the voltage with variations of 10 volts, 20 volts and 30 volts with a current strength of 1 ampere. The electrocoagulation process takes place with a variety of contact times of 30 minutes, 45 minutes and 60 minutes. After the electrocoagulation process is complete, the solution is allowed to settle, then the sample is taken by filtering using filter paper.

Phosphate analysis in laundry wastewater refers to SNI 06-6989.31-2005, using the uv-vis spectrophotometric method in ascorbic acid. After the filtration process, take a portion of the filtrate sample to analyze the phosphate concentration. Add ammonium molybdate and ascorbic acid reagents to the sample according to the standard procedure of SNI 06-6989.31-2005. The mixture was then incubated for 15 minutes to form a blue complex. After that, measure the absorbance of the solution using a UV-Vis spectrophotometer with a wavelength of 880 nm. Compare the absorbance value obtained with the phosphate standard calibration curve to determine the final phosphate concentration in the sample [24].

3. Results and discussion

3.1. Initial parameters

Samples of laundry wastewater without treatment were tested for phosphate concentration using a UV- Vis spectrophotometer to compare phosphate concentrations before (see Table 2) and after the electrocoagulation process. Based on the initial phosphate concentration test on the laundry wastewater sample, the result is 0.227 mg/L, meaning that this result exceeds the quality standard set by the Government Regulation of the Republic of Indonesia Number 22 of 2021 for phosphate concentration in class 1 and 2 river water, which is 0.2 mg/L.

3.2. Analysis of phosphate concentration decrease after electrocoagulation

Electrocoagulation works on the principle of redox reaction (reduction and oxidation). In an electrocoagulation cell system, oxidation occurs at the positive electrode or anode, while reduction reactions occur at the negative electrode or cathode [25]. The effectiveness of the electrocoagulation process is greatly influenced by various operational parameters such as pH, current density, type and spacing of electrodes, treatment time, as well as stirring speed, where optimized settings of these parameters can significantly increase the pollutant removal efficiency of wastewater [18], [22]. Table 3 shows the research results of the effect of voltage variation and contact time of the electrocoagulation process.

Table 3 shows that increasing the voltage and contact time has an effect on reducing the phosphate concentration in laundry wastewater. Gradually, the phosphate concentration decreased, and the phosphate removal efficiency increased as the voltage and contact time of electrocoagulation increased. However, increasing the voltage or extending the contact time only gave a relatively small increase in efficiency. This could be due to the reaching of the reaction saturation point, where most of the phosphate has been coagulated and only a very small amount remains, so that adding voltage or contact time no longer has a significant impact. Each treatment combination was only performed once (without replication). This did not allow the ANOVA significance test to be conducted. So, the interpretation of differences between treatments (voltage and contact time) can only be descriptive.

Based on Fig. 2, the relationship between voltage variation and electrocoagulation contact time on the reduction of phosphate concentration in laundry wastewater after electrocoagulation treatment was determined. Generally, the phosphate concentration decreased significantly by the 30th minute, particularly at higher voltages. A voltage of 30 volts resulted in the greatest reduction, from 0.277 mg/L to 0.015 mg/L, followed by 20 volts with a reduction to 0.064 mg/L, and 10 volts with a reduction to 0.116 mg/L. This indicates that, in the early stages, higher voltages accelerate floc formation by releasing metal ions from the electrode, which act as coagulants to destabilize phosphate particles. The chemical reactions occurring at the aluminum electrodes under direct current are presented in Eqs. (1), (2), (3), and (4).

$$2\ \mathrm{Al} \rightarrow 2\ \mathrm{Al}_3 +\ 6\ e^- \tag{1}$$

$$6\ H_2O + 6\ e^- \rightarrow 6\ OH^- + 3\ H_2 \tag{2}$$

$$2\ \mathrm{Al} + 6\ H_2O \rightarrow 2\ Al(OH)_3 + 3\ H_2 \tag{3}$$

$$Al^{3+} + H_nPO4^{3-n} \rightarrow AlPO_4 + nH^+ \tag{4}$$

Equation (1) describes the oxidation reaction at the anode, while Equation (2) describes the reduction reaction at the cathode. Equation (3) represents the overall reaction, and Equation (4) illustrates the formation reaction of aluminum phosphate with phosphate contained in laundry wastewater.

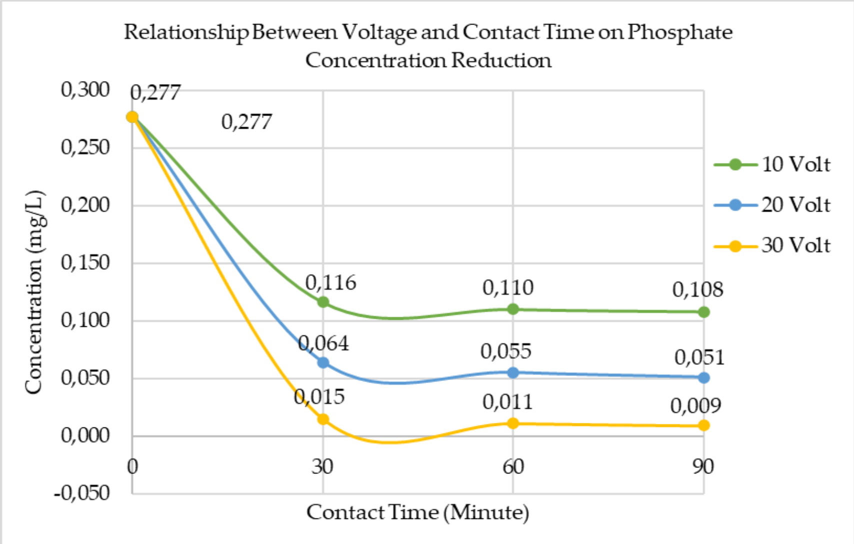

Fig. 2. Relationship between voltage variation and contact time on phosphate concentration reduction.

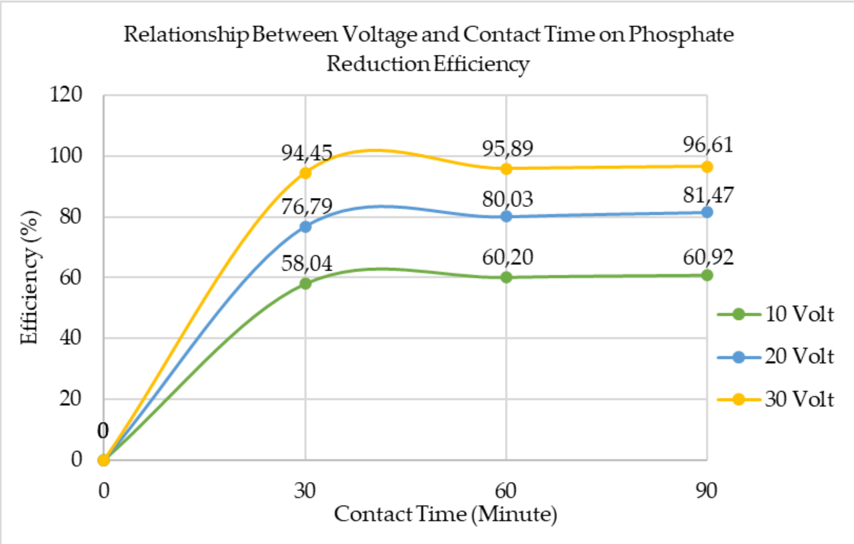

Fig. 3. Relationship between voltage variation and contact time on phosphate reduction efficiency.

In the electrocoagulation system, the aluminum electrode that functions as the negative pole (cathode) undergoes a redox reaction that produces OH^- ions and hydrogen gas (H_2). Meanwhile, the aluminum electrode that acts as an anode (positive pole) undergoes an oxidation reaction that releases aluminum ions (Al^{3+}) into the solution. Al^{3+} ions then interact with OH^- ions and produce aluminum hydroxide ($Al(OH)_3$), a compound that has basic properties.

The resulting aluminum hydroxide functions as a coagulant and reacts with phosphate ions in laundry wastewater to form aluminum phosphate flocs or precipitates ($AlPO_4$). These flocs are pushed to the surface of the solution by H_2 gas formed at the cathode, then the flocs meet each other and join to form larger flocs. The flocs that have joined will settle to the bottom when their density exceeds the density of the solution, so that the phosphate concentration in laundry wastewater decreases [26]. Using [27], the efficiency of reducing phosphate concentration before and after the electrocoagulation process can be calculated using Eq. (5),

$$Efficiency = \frac{C_O - C_f}{C_O} \times 100\% \qquad (5)$$

where C_O is initial concentration (mg/L) and C_f is final concentration (mg/L).

Based on Fig. 3, the relationship between voltage variation and contact time on phosphate reduction efficiency was obtained. At a voltage of 30 volts, there was a very significant increase in efficiency, which reached 94.45% at the 30th minute, then increased to 95.89% at the 60th minute, and reached the highest efficiency of 96.61% at the

90th minute. These results indicate that the longer contact time and higher voltage in electrocoagulation improve phosphate removal efficiency [28].

As a supporting study, research by Takdastan et al. [29] mentioned that, at a contact time of 90 minutes, the phosphate removal efficiency increased from 73% at a voltage of 10 volts to 100% at a voltage of 30 volts using aluminum electrodes. Meanwhile, research by Ramadhan et al. [30] stated that, at a contact time of 60 minutes, the removal efficiency reached 72% at a voltage of 9 volts and increased to 92% at a voltage of 15 volts using aluminum electrodes. This shows that the optimal setting of voltage and contact time parameters plays an important role in the performance efficiency of the electrocoagulation process in the treatment of wastewater containing phosphate. However, the differences in experimental results between studies may occur due to various influencing factors, including the applied electric current (applied voltage), distance between electrodes, configuration of electrode, acidity of the solution, ion concentration at the start of the process, materials used for anodes and cathodes, type of water being treated, conductivity of the solution, temperature, hydrolysis time, sodium chloride concentration [31].

The findings of this study can be applied in the laundry industry as an efficient wastewater treatment solution by integrating an electrocoagulation system into existing operations, especially for small to medium-sized businesses that often lack proper wastewater management. The high phosphate removal efficiency and low environmental impact make electrocoagulation a promising alternative to conventional methods. In addition, the simplicity of the equipment, minimal chemical usage, and reduced sludge production present significant opportunities for commercial implementation.

4. Conclusions

The highest electrocoagulation efficiency was achieved at a voltage of 30 volts and a contact time of 90 minutes with a decrease in phosphate concentration of up to 96.61%, from an initial concentration of 0.277 mg/L to 0.009 mg/L. These results indicate that increasing the voltage and contact time accelerates floc formation and increases the efficiency of phosphate precipitation. Electrocoagulation is able to reduce the phosphate concentration to under the threshold set in the Government Regulation of the Republic of Indonesia No. 22 of 2021, which is 0.2 mg/L for class I and II which regulates the quality standard of phosphate concentration in river water. The results show that electrocoagulation is an effective and environmentally friendly laundry wastewater treatment method compared to conventional coagulation, because it requires no addition of chemicals and produces less sludge.

This study has a limited scope, as the efficiency testing of the electrocoagulation method only focused on reducing the phosphate concentration of one type of laundry wastewater and using one type of electrode only. Therefore, further studies need to consider the use of a wide variety of electrode materials, testing various types and sources of wastewater, as well as a more comprehensive evaluation of energy consumption and cost efficiency.

Declaration statement

Dhara Yuniar: Planning, Data Collection, Analysis of Results, Editing and Writing the Original Draft. **Agung Sugiharto:** Evaluate Methodology and Proofread Draft.

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Disclosure statement

The authors declare that this manuscript is free from conflicts of interest and has been prepared in accordance with the provisions and policies of the applicable publication ethics, in order to prevent ethical deviations in various forms.

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Data availability statement

The authors acknowledge that all data on which the results of this study are based can be found in the article and supporting materials.

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