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Statistical Optimization of Vegetable Washwater Treatment Using Electrocoagulation

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ABSTRACT

This study investigates the application of electrocoagulation (EC) for treating vegetable washwater (VWW). Preliminary EC experiments were carried out to define the operational parameter ranges supporting a subsequent statistical optimization of the process. The optimization aimed to identify the most efficient operating conditions for pollutant removal while minimizing energy consumption. VWWs were sampled from four root vegetable washings (potatoes, leeks, and red beets). Various EC tests carried out using a 500-mL reactor and a response surface methodology of experiments enabled us to obtain optimum operating conditions for the treatment of VWW. Thus, optimal conditions of a current intensity of 0.32 A for 8.8 min with aluminum electrodes gave total suspended solid (TSS) and turbidity reduction rates of 99% and 98%, respectively, along with a total phosphorus reduction rate of 93% for *Farm 1*. EC VWW treatment generally met the regulatory discharge limit of 50-mg/L TSS. Only TSS of *Farm 4* remained well above the limit. EC also reduced neonicotinoid insecticides present in VWW by 38%, and the true color of beet roots decreased from 283 to 60 UCV. The energy costs associated with VWW clarification treatment ranged between CAD\$0.06/m³ and CAD\$0.09/m³.

1 | Introduction

The growing demand for pre-washed and ready-to-eat fruits and vegetables has prompted farmers and food packaging companies to wash produce before it reaches the market. This high consumption of fruits and vegetables contributes to a growing demand for drinking water and thus increases the risk of water shortages. The agri-food sector, and more specifically the vegetable industry, is among the activities that consume significant volumes of water. In Quebec, there are approximately 150 fruit and vegetable washing stations that produce over 4.8 million m³ of wastewater annually (Pelletier et al. 2015). It has been investigated that postharvest processing of fruit, leafy greens,

or root vegetables generates 5 L of wastewater per kilogram of produce (Zytner 2020). Following harvest, fruits and vegetables are washed to remove soils, fertilizers, and pesticides. Moreover, these products often undergo additional processing, including cutting, peeling, sanitization, and packaging. Water is also used to transport these products within the facility (Mundi et al. 2017).

The wastewater released from the washing process is called washwater. Fruit and vegetable producers and processors are trying to find a cost-effective way to reduce freshwater consumption in the washing process. Moreover, the washwater should be treated before disposal or recycling to reduce environmental

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Summary

- Vegetable washwater contains high TSS and pesticides.
- Electrocoagulation achieved 99% TSS and 98% turbidity removal.
- Total phosphorus reduced by 93% under optimal EC conditions.
- Neonicotinoid insecticides reduced by 38% using EC.
- Energy cost of EC treatment was only CAD\$0.06–0.09/m³.

impacts, because it contains high levels of organic matter from peeling processes, nitrogen compounds, phosphorus, heavy loads of solids, including microorganisms, as well as dissolved and suspended matter (Zytner and Warriner 2016). The treatment process should lead to producing water that meets the rejection or reuse standards. In Quebec (Canada), for example, the total suspended solid (TSS) concentration in VWW must not exceed 50 mg/L prior to discharge (Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs [MELCCFP] 2020). Although vegetable washwaters (VWWs) represent a significant source of environmental contamination, the appropriate treatment technologies remain underexplored. Among these, electrocoagulation (EC) emerges as a promising solution for solid–liquid separation and reduction of organic pollutants, thanks to the in situ generation of metallic coagulants. Nonetheless, research on the use of EC for VWW treatment is very scarce. To date, only the study conducted in Ontario has evaluated the feasibility of EC for the treatment of VWW, demonstrating a substantial reduction in turbidity and solids (Zytner and Warriner 2016).

EC is an innovative process notable for its effectiveness and adaptability in treating agricultural wastewater. EC is emerging as an efficiency alternative to conventional techniques, such as chemical coagulation and membrane filtration, because of its versatility in removing a wide range of pollutants and reduced ecological footprint. This process involves dissolving metal electrodes, typically iron or aluminum, to generate local metal hydroxides that remove impurities through adsorption, complexation, or precipitation (Al-Marri et al. 2023; Ammar et al. 2023).

Very few studies mention the presence of pesticides in VWW. Research carried out on the waterways around the regions where potatoes are grown in Quebec has shown that neonicotinoid insecticides such as thiamethoxam (TMX), clothianidin (CLO), and imidacloprid are widely used by potato farmers in the province. In the study by Giroux and Fortin (2010), 80% of the collected samples contained pesticides. According to John et al. (2016), the EC is able to remove up to 97.6% of acetamiprid, a neonicotinoid insecticide. Furthermore, in their literature review on the state of knowledge in VWW management, Tanoe et al. (2025) propose electrochemical processes to permanently eliminate pesticides. For example, the EC is successful in assembling organic, inorganic, and microbial pollutants into flocculated particles, which are easier to separate from clarified water (Daghrir et al. 2013; Drogui et al. 2008; Hand and Cusick 2021).

To ensure eco-responsible water management and comply with increasingly stringent regulatory standards, Quebec vegetable producers require efficient, automated, and cost-effective treatment technologies. Our study evaluated the effectiveness of EC for the decontamination of root VWW. Statistical analysis is applied in this research to optimize the EC treatment of water used for washing vegetables. The main objective was to optimize the treatment effectiveness while reducing energy costs and sludge production. The influence of current intensity, electrolysis time, and electrode type on the reduction of turbidity and TSSs in VWW was examined. The findings of this study will provide valuable information for the large-scale implementation of efficient and innovative EC systems in the agricultural industry.

2 | Methodology

2.1 | Sampling and Characterization of Different VWWs

Four samples of VWWs from different farms in Quebec (Canada) were sampled and characterized. *Farm 1* produced wastewater from washing red potatoes grown on sandy loam. After passing through a coarse filter, the water entered a transfer basin and was collected at the inlet of a system of two nonaerated lagoons arranged in series. *Farm 2* generated wastewater from washing white potatoes grown on loamy sand; the effluent from the washing machine passed through two successive settling tanks (hydraulic residence time: 3 h each) before discharge, and the sample was taken at the outlet of the second tank. *Farm 3*, producing leeks on clay loam, treated its wastewater through a settling tank followed by a nonaerated lagoon (hydraulic residence time: 2 h); sampling occurred at the outlet of the settling tank, before the lagoon. *Farm 4*, producing red beets on mineral loam, had its wastewater collected directly at the exit of the washing machine. At this farm, wastewater normally flows to a nonaerated lagoon (hydraulic residence time: 14 h) before discharge into a nearby stream.

All samples were collected in polypropylene buckets and stored at 4°C until analysis. The wastewater was sampled at different times throughout the study, and its initial characteristics varied over time. Concentrations of neonicotinoids (CLO and TMX) were analyzed in the VWW for potatoes, red beets, and red leeks.

The initial characterization of VWW was carried out using a variety of techniques. The pH and conductivity were monitored using a pH/conductivity meter (Oakton Model 510). TSSs and total solids were measured in triplicates per standard procedures of the Centre d'expertise en analyse environnementale du Québec (CEAEQ 2015, 2017). Turbidity was measured using a Hach 2100AN turbidimeter calibrated with standard solutions ranging from 20 to 4000 NTU. Chemical oxygen demand (COD) was measured with a colorimetric method using Hach COD tubes in the range of 0–1500 mg/L (CEAEQ 2016). With a Lachat autoanalyzer, ammonium (NH₄) was measured with a salicylate-hypochlorite colorimetric method (CEAEQ 2014). Residual color concentrations (true color) were determined in conformity with the standard method MA. 103—Col. 2.0 (CEAEQ 2023) and using a Cary 50 UV spectrophotometer (Varian Canada, Mississauga, Canada). The analysis of metals

TABLE 1 | Characterization of vegetable washwaters and some permissive levels.

	Vegetable washwaters					Permissive levels				
	Farm 1	Farm 2	Farm 3	Farm 4	Canada		The United States ^d	Lithuania ^e	Finland ^f	
					Quebec ^a	Ontario ^c				
Vegetables	Red potatoes	White potatoes	Leeks	Red beets	VWW	VWW	Agri-food WW	Farm WW	Farm WW	
Crops soils	Sandy loam	Loamy sand	Clay loam	Mineral loam	—	—	—	—	—	
pH, mean ± SD	7.2 ± 0.4	7.1 ± 0.2	6.5 ± 0.2	7.5 ± 0.2	—	—	6.0–9.0	6.5–8.4	—	
Conductivity (µS/cm), mean ± SD	795 ± 28	508 ± 8	95 ± 0.2	695 ± 10	—	—	—	—	—	
Turbidity (NTU), mean ± SD	246 ± 21	468 ± 35	1105 ± 78	2467 ± 114	—	—	—	700	—	
COD (mg/L), mean ± SD	145 ± 32	83 ± 13	97 ± 15	479 ± 82	—	—	—	125	< 250	
BOD	—	—	—	—	—	25	45	4–6	< 30	
TSS (mg/L), mean ± SD	215 ± 41	495 ± 154	2193 ± 236	1957 ± 398	50	—	45	25	—	
TS (mg/L), mean ± SD	223 ± 15	724 ± 31	3957 ± 76	2377 ± 234	—	—	—	—	—	
True color (UCV), mean ± SD	—	—	—	283 ± 27	15 ^b	—	—	—	—	
N-NH ₄ (mg/L), mean ± SD	0.7 ± 0.1	1.3 ± 0.2	0.08 ± 0.02	2.3 ± 0.4	—	< 1	—	—	< 10	
Total phosphorus (mg/L), mean ± SD	1.4 ± 0.4	14 ± 0.2	< 0.55	4.2 ± 0.3	0.3	< 0.3	—	2	< 2	
Fecal coliforms (CFU/100 mL), mean ± SD	—	—	—	—	—	—	400	—	—	
Thiamethoxam (µg/L), mean ± SD	0.71 ± 0.01	—	0.02 ± 0.01	< 0.002	0.0083	—	—	—	—	
Clothianidin (µg/L), mean ± SD	0.25 ± 0.01	—	0.1 ± 0.01	< 0.002	0.0083	—	—	—	—	
S-Metolachlor (µg/L), mean ± SD	0.55 ± 0.01	—	0.62 ± 0.001	—	7.8	—	—	—	—	
Chlorantraniliprole (µg/L), mean ± SD	0.013 ± 0.001	—	—	—	0.22	—	—	—	—	

^aMinistère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs (2023).
^bVille de Québec (2019). City of Québec. It does not exist clearly discharge standards color for the province of Québec.
^cOntario Ministry of Environment (1994).
^dUnited States Environmental Protection Agency (USEPA 2025) and Pailthorp et al. (1987).
^eDapkienė et al. (2017).
^fBaltic Marine Environment Protection Commission (1996).

and total phosphorus (TP) was carried out using Agilent's 5110 Dual View ICP-OES (Agilent Technologies, Australia) following the United States Environmental Protection Agency (USEPA) method 200.7 (USEPA 2001). Anions were analyzed by ion chromatography using an IonPac AS11-HC 4- μm resin ion exchange column and Thermo's Integriion HPIC (CEAEQ 2025). Pesticides, such as CLO, TMX, *S*-metolachlor, and chlorantraniliprole, were analyzed by liquid chromatography–tandem mass spectrometry (LC–MS/MS) following the MA. 403—Pest_émergent method (Ministère de l'Environnement et de la Lutte contre les changements climatiques 2020). The initial characteristics of each of the VWW, along with some permissive limits, are presented in Table 1.

2.2 | Experimental Unit—Electrolytic Cell

EC experiments were conducted in batch mode using a Plexiglas, rectangular reactor with internal dimensions of 4 cm (width), 12 cm (length), and 16 cm (height), providing a working volume of 0.5 L (Figure 1). Each test employed two flat rectangular electrodes, one serving as the anode and the other as the cathode, each with an active surface area of 110 cm² (11 × 10 cm, 1 mm thick), spaced 1 cm apart. The electrodes were connected in a monopolar configuration to a direct current power supply (Extech Instruments, Montréal, Canada). To allow for proper mixing, the electrodes were suspended vertically without contacting the reactor bottom, supported by a perforated Plexiglas plate positioned 2 cm above the base. Mixing within the cell was ensured by a Teflon-coated stirring rod placed between the support plate and the reactor bottom.

Table 1 indicates the initial physicochemical characteristics of VWW and the guidelines from Canada (Quebec and Ontario), the United States, Lithuania, and Finland for effluent discharge in the urban sewage works and watercourses. This approach made it possible to contextualize the performance of the EC process not only within the regulatory framework of Quebec but also in relation to other jurisdictions. Discharge limits for specific contaminants vary by region, reflecting differences in climate conditions, available technologies, the sensitivity of receiving environments, and regional environmental priorities (UN Habitat and World Health Organization [WHO] 2021). A review of regulatory thresholds shows that only the guidelines issued by MELCCFP include limits for neonicotinoid insecticides. Among the parameters analyzed in the VWWs, TSSs, turbidity, TP, TMX, and CLO exceeded

the maximum values recommended by the MELCCFP. Therefore, these specific parameters were monitored during the experiments to assess the effectiveness of the EC process in treating the different samples of VWW.

2.3 | Experimental Procedure

2.3.1 | Preliminary Tests

Based on previous work on the electrochemical treatment of VWW, the anode and cathode were provided with two pairs of electrodes, namely, aluminum/aluminum (Al) and then iron/iron (mild steel; Fe) for preliminary tests (Khajvand 2021; Mundi et al. 2017). The objective of the preliminary tests was to evaluate the effectiveness of TSSs and turbidity removal using EC under two current intensities (0.5 and 1.0 A), a fixed treatment time of 30 min, and two types of sacrificial anodes (iron and aluminum). The anode and cathode sets were connected, respectively, to the positive and negative outlets of the power supply. Washwater from *Farm 1* was used for these preliminary tests. This resulted in a total of four experimental runs for both electrode types (two tests for the aluminum electrodes and two tests for the iron electrodes). Given that the conductivity of the washwater samples exceeded 100 $\mu\text{S}/\text{cm}$, no Na_2SO_4 was added to facilitate the EC process. At the end of each run, the treated water was allowed to settle for 1 h. The supernatant was carefully collected using a mechanical pipette at a fixed depth from the surface and then submitted to water quality analyses. This settling and supernatant recovery procedure was applied to all electrocoagulated samples presented in this study.

All experiments were conducted at ambient temperature ($20 \pm 2^\circ\text{C}$). Between successive tests, the electrolytic cell was cleaned with a 5% (v/v) sulfuric acid solution for at least 10 min, followed by thorough rinsing with distilled water. Electrodes were manually scrubbed with a sponge and rinsed again with distilled water to prevent surface passivation, as recommended by Aoudjehane et al. (2010) and Robinson (1999). The amount of metal dissolved by anodic oxidization was calculated using Faraday's law in Equation (1).

$$\text{Amount of electrode dissolution} = \frac{I \cdot t \cdot M_w}{z \cdot F \cdot v} \quad (1)$$

where I is the current intensity (A), t is the treatment time (s), M_w is the molecular weight of the electrode (26.98 g/mol for Al and 55.85 g/mol for Fe), z is the number of electrons transferred (3 for Al and 2 for Fe), F is Faraday's constant (96,485 C/mol), and v is the volume of liquid treatment (m³).

2.3.2 | Experimental Design Methodology

An experimental design based on response surface methodology (RSM) was used for modeling and analyzing the EC process for VWW treatment. In this study, the factorial design (FD) and the central composite design (CCD) were applied successively. FD is used to determine the relationship between independent variables (or factors) and the dependent variables. The FD was firstly used to investigate the main effects and interaction effects of factors

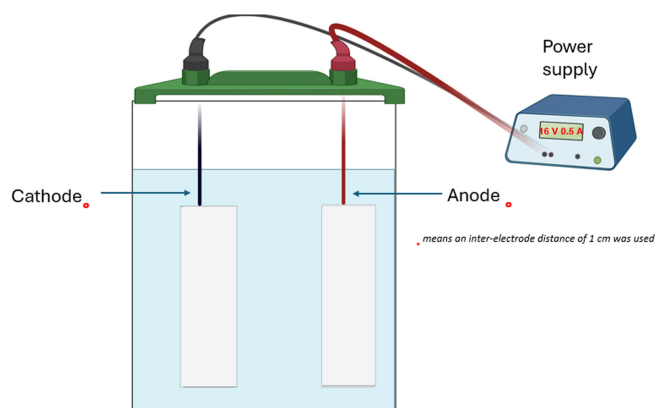


FIGURE 1 | Electrocoagulation experimental unit.

TABLE 2 | Experimental range and levels of process independent variables.

Coded variables (X_i)	Factor (U_i)	Experimental field		$U_{i,0}$	ΔU_i
		Min. value (−1)	Max. value (+1)		
X_1	U_1 : Current intensity (A)	0.2	1	0.6	0.4
X_2	U_2 : Electrolysis time (min)	2	10	6	4
X_3	U_3 : Type of electrode	Al	Fe	—	—

on the elimination of TSS and turbidity, as well as the consumed energy associated with EC treatment. Three independent factors were selected based on preliminary tests: current intensity (U_1), electrolysis time (U_2), and anode material (U_3). The responses were suspended solids removal rate (Y_1), turbidity removal rate (Y_2), and energy consumption (Y_3). Table 2 shows the experimental area, the levels of independent variables, and their limits of variation. The parameters X_1 , X_2 , and X_3 represent the coded variables. It is worth noting that this factorial (2^3) design model cannot be used to identify the optimal conditions. CCD methodology was then applied to identify the best conditions for TSS and turbidity removal. In addition to the factorial matrix (Tests 1–8), 18 tests were carried out (Tests 9–26). Two categorical factors (Al and Fe anode material) were used, and for each anode material, nine additional experiments were required. Five runs were carried out at the center of the experimental region investigated for each anode material.

It is important to note that EC process was firstly applied and optimized for the treatment of VWV coming from *Farm 1*. The optimal conditions were applied for the treatment of other VWV coming from *Farm 2*, *Farm 3*, and *Farm 4*, respectively. Under the optimal condition, the performances of the EC process to remove neonicotinoid insecticides (CLO and TMX) were evaluated. The effectiveness of EC process to remove simultaneously TP (P_i) and true color (only for *Farm 4*) was also evaluated.

The removal efficiency of the parameters after treatment was calculated according to Equation (2).

$$R = \frac{C_i - C_f}{C_i} \times 100 \quad (2)$$

where C_i and C_f represent respectively the initial and final concentrations of the target pollutant.

2.4 | Economic Analysis

The economic analysis included energy consumption, electrode consumption, and the cost of metallic sludge disposal. In Quebec, the cost of energy consumption was estimated at CAD\$0.09/kWh (Kiendrebeogo et al. 2021). The mild steel

electrode consumption was evaluated at a cost of CAD\$0.0165/kg (Bérard and Jémus 2025), whereas a cost of CAD\$5.73/kg was considered for the aluminum electrode (Mercier 2025). The disposal costs for the residual sludge, including transportation and the charge for waste disposal, were evaluated at CAD\$0.070/kg of wet residue by assuming that these metallic residues were not considered hazardous (Asselin et al. 2008). Total cost was evaluated in terms of Canadian dollars spent per cubic meter of treated VWV (CAD\$/m³).

3 | Results and Discussion

3.1 | Effectiveness of EC Process in Treating VWV Coming From Farm 1 (Preliminary Tests)

Table 3 summarizes the initial and final conditions of each assay, as well as the recorded removal efficiencies for TSS and turbidity in wastewater from the washing of red potatoes cultivated on sandy loam (*Farm 1*). Power consumption during these tests ranged from 7.7 to 24 kWh/m³, and the generation of metallic sludge varied between 0.6 and 2.1 kg/m³, with higher amounts observed when using iron electrodes. Regardless of the electrode material, energy consumption increased significantly when the current intensity rose from 0.5 to 1 A. However, the energy consumption for the iron and aluminum electrodes was almost the same at a constant current intensity. The escalation in energy consumption during EC is affected by the augmentation of current intensity, irrespective of the electrode material employed (Alilou and Fathali 2024; Sanou et al. 2023). During EC, energy consumption (E) fundamentally relies on the electrical power ($P = V \cdot I$) supplied to the current generator, as expressed by the following formula:

$$\text{Energy consumption} = \frac{V \cdot I \cdot t}{v} \quad (3)$$

where V is the voltage (V), I is the current intensity (A), t is the treatment time (s), and v is the volume of liquid treatment (m³).

Under the tested conditions, iron electrodes exhibited greater anodic dissolution compared to aluminum electrodes, as confirmed by the mass of electrode material dissolved: 0.52–1.04 kg/m³ for Fe and 0.17–0.34 kg/m³ for Al.

The performance of the EC process in terms of TSS and turbidity removal was influenced by both the anode material and the applied current intensity (Drogui et al. 2008; Yu et al. 2025). Among the conditions tested, the use of aluminum electrodes at a lower current intensity (0.5 A) yielded the best results, achieving up to 99% turbidity removal and 94% TSS removal, superior to the performance observed with iron electrodes at either current intensity. In EC, the coagulation mechanisms differ from one metal electrode to another, which could explain the differences in performance observed between Al and Fe electrodes. The anodic dissolution of aluminum generates Al³⁺ ions that quickly hydrolyze into amorphous hydroxides (e.g., Al(OH)₃), characterized by a strong adsorption and destabilization capacity of colloidal particles (Guvenc et al. 2017). These species effectively promote the neutralization of negative charges, the growth of dense flocs, and their rapid sedimentation, which results in high turbidity and TSS removal

TABLE 3 | Results from preliminary tests after the treatment of wastewater coming from a washing operation of red potatoes cultivated on sandy loam (Farm 1) using aluminum (Al) and mild steel (Fe) electrodes.

Parameters	Aluminum (Al)		Mild steel (Fe)	
Current intensity (A)	0.5	1.0	0.5	1.0
Time (min)	30	30	30	30
Voltage (V)	16.90	24.90	15.40	23.90
Initial conductivity (mS/cm)	0.80	0.80	0.80	0.80
Initial pH	7.20	7.20	7.20	7.20
Final pH	7.20	6.90	9.20	8.30
Energy consumption (kWh/m ³) ^a	8.50	24.90	7.70	23.90
Sludge produced (kg/m ³) ^a	0.60	0.70	1.50	2.10
Electrode dissolved (g) ^b	0.08	0.17	0.26	0.52
Electrode dissolved (kg/m ³) ^a	0.17	0.34	0.52	1.04
Energy costs (\$/m ³) ^a	0.76	2.24	0.69	2.15
Disposal cost (\$/m ³) ^a	0.042	0.049	0.105	0.147
Electrode costs (\$/m ³) ^a	0.97	1.94	0.08	0.17
Total cost (\$/m ³) ^a	1.77	4.23	0.88	2.47
Initial TSS (mg/L)	215	215	215	215
Final TSS (mg/L)	12.4	84.4	22.4	63.6
TSS removal (%)	94	61	90	70
Initial turbidity (NTU)	246	246	246	246
Final turbidity (NTU)	3.0	48.2	15.4	67.1
Turbidity removal (%)	99	80	94	73

^aPer unit volume of treated water.

^bSee Equation (1).

rates, as observed with the aluminum electrode at 0.5 A (up to 99% reduction in turbidity and 94% reduction of TSS under the conditions tested). Iron electrodes produce Fe²⁺ and Fe³⁺ ions that hydrolyze mainly into Fe(OH)₂ and Fe(OH)₃, which are more crystalline and less amorphous coagulants than aluminum hydroxides. Although the iron electrodes showed higher anodic dissolution, this does not necessarily translate into better performance. Excessive dissolution can lead to overproduction of sludge or formation of heavier but less reactive flocs (Hertiani and Yuniarto 2025).

Literature suggests that the effectiveness of anode materials in EC can be affected by pH: Aluminum hydroxides (Al³⁺ → Al(OH)₃) are generally more effective in neutral to slightly alkaline media because of their fine particle size, which promotes colloid destabilization and rapid floc formation (Al-Marri et al. 2023; Bako et al. 2021).

The lowest residual TSS concentration (12.4 mg/L) was obtained with the aluminum electrode, a value four times lower than the discharge limit set by Quebec's Ministry of the Environment for effluent released into storm sewers or water bodies. These results highlight the significant influence of electrode material, current intensity, and treatment time on EC performance. It would therefore be valuable to further investigate the individual and combined effects of these parameters on TSS and turbidity removal, while also seeking to optimize energy consumption. These initial tests also served to define the appropriate ranges for the independent variables to be used in subsequent experimental phases involving FD and CCD methodologies.

3.2 | Effect of Experimental Parameters on TSS and Turbidity Removal in Treating VWW Coming From Farm 1 Using FD Methodology

After identifying the range of the independent process variables, we evaluated the influence of three parameters: current intensity (U_1), electrolysis time (U_2), and type of anode (U_3) on the efficiency of TSS and turbidity removal using the experimental design methodology by means of a factorial matrix (2^k). The influence of each factor and their two-way interactions were systematically assessed. The experimental values of " U_i " (see Table 2) were calculated from the " X_i " variables using Equation (4).

$$X_i = \frac{U_i - U_{i,0}}{\Delta U_i} \quad (4)$$

where $U_{i,0} = (U_{i,\max} + U_{i,\min}) / 2$ represents the value of U_i at the center of the experimental range and $\Delta U_i = (U_{i,\max} - U_{i,\min}) / 2$ represents the variation step. $U_{i,\max}$ and $U_{i,\min}$ are respectively the maximum and minimum values of the effective variable U_i .

The experimental response can be represented by a linear polynomial model with the following interaction:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 \quad (5)$$

where Y represents the experimental response, and X_1 , X_2 , and X_3 represent the coded variables. The coefficients b_1 , b_2 , and b_3 represent the estimation of the principal effect of the factors. The coefficients b_{12} , b_{13} , and b_{23} represent the estimation of the interaction effect between the factors. These coefficients were calculated by means of Design-Expert program software (Design-Expert 7 2007, Stat-Ease Inc., Minneapolis). The responses Y_1 , Y_2 , and Y_3 are respectively the turbidity removal, the TSS removal, and the energy consumption.

$$Y_1 = 70 + 6.75X_1 + 2.00X_2 - 18.50X_3 + 4.50X_1X_2 + 4.00X_1X_3 - 4.75X_2X_3 \text{ (turbidity)} \quad (6)$$

$$Y_2 = 74 + 2.62X_1 + 5.37X_2 - 8.63X_3 - 2.12X_2X_3 \text{ (TSS)} \quad (7)$$

$$Y_3 = 2.46 + 2.20X_1 + 1.70X_2 - 0.28X_3 + 1.53X_1X_2 - 0.26X_1X_3 - 0.20X_2X_3 \text{ (energy consumption)} \quad (8)$$

The responses (Y_1 , Y_2 , and Y_3) recorded are respectively well fitted to the polynomial models with at least a regression coefficient R^2 of 0.99. The coefficients $b_0 = 70$ (for turbidity removal) and $b_0 = 74$ (for TSS removal) represent the average value of the response (Y_1 and Y_2) of the eight FD tests. By considering TSS for which a permissive level has been imposed by Québec City and the USEPA for effluent discharge, TSS removal is influenced by the type of anode material ($b_3 = -8.63$). This factor (X_3) has a negative effect on the TSS removal. The percentage of TSS removal decreases on average by 17.3% (2×8.63) when the anode material passes from Al to Fe. The second most important factor in the TSS removal is the period of electrolysis with a positive effect ($b_2 = +5.37$). The increase of electrolysis time contributes to the increase in the percentage of TSS removal. The percentage of TSS removal increases on average by 10.7% (2×5.37) when the period of electrolysis goes from 2 to 10 min. By comparison, the effects of the current intensity ($b_1 = +2.62$) are relatively low, and the current intensity effect is positive.

The FD matrix and corresponding results are shown in Table 4. Assay 6 (Al, 1 A and 10 min) produced the best turbidity (96%) and TSS (93%) removal.

The importance of the factors and interactions can be discussed using graphical Pareto analysis. Pareto analysis gives more significant information to interpret the results. By focusing on the most important elements, Pareto analysis simplifies understanding (Kumar et al. 2020). Indeed, this analysis calculates the percentage (P) effect of each factor on the response, according to the following relation:

$$P = \left(\frac{bi^2}{\sum bi^2} \right) \times 100 \quad (i \neq 0) \quad (9)$$

where bi stands for the estimation of the main effect of factor i on a given response.

The importance of the three selected factors and their interactions was highlighted by evaluating their contribution to TSS removal, turbidity removal, and energy consumption. The contributions (P) are shown in Figure 2.

TSS removal is mainly influenced by the type of electrode (62% contribution) and electrolysis time (24% contribution). In comparison, current intensity contributes only 6% for TSS removal. Turbidity removal from VWW is mainly influenced by electrode type (70%), whereas electrolysis time contributes 0.88% and current intensity 9.3% to turbidity removal. Finally, energy consumption related to EC treatment of VWW is mainly influenced by current intensity (47%), electrolysis time (28%), and the combined effect of current and time (23%).

For TSS removal, one of the largest contributions of the interaction effects was recorded with X_2X_3 (electrolysis time–electrode material). The explanation of the interactions X_2X_3 can be facilitated by plotting Figure 3. In this figure, each summit of the square represents a combination of the levels of the two factors. The value of 90.0% indicated in the left corner is recorded by calculating the average of the experimental results from the tests carried out with the Al electrode by imposing a treatment time of 10 min (Tests 5 and 6).

When the electrode material (variable X_3) is fixed at the lowest level (by using Al), the treatment time (X_2) does not have a highly significant influence on the response; the percentage of TSS removal passes from 86.5% to 90% for 2 and 10 min, respectively. If the electrode material is fixed at the highest level (by using Fe), the treatment time has a significant influence on TSS removal. It was more important than the first case while using Al material. The average of the percentage of TSS removal decreased from 68.5% to 62%.

Thus, the effect of electrolysis time is not constant; it depends on the type of anode material under our experimental conditions.

The type of anode and the intensity of the applied current have a significant influence on turbidity removal. Figure 4 illustrates the interaction between these two factors. The top of each square represents a combination of levels of the two factors (current intensity and electrode type). Each corner of the square represents a specific combination of current intensity and electrode type. For instance, the upper right corner corresponds to a current intensity of 1.0 A combined with iron electrodes. The value of 62.0%, displayed in the

TABLE 4 | Experimental factorial matrix in the 2^3 design and experimental results.

Tests	Experimental design			Experimental plan			Experimental responses		
	X_1	X_2	X_3	U_1 (A)	U_2 (min)	U_3	Turbidity removal (%)	TSS removal (%)	Energy consumption (kWh/m ³)
1	−1	−1	+1	0.2	2	Fe	54	62	0.10
2	+1	−1	+1	1.0	2	Fe	54	62	1.26
3	+1	+1	+1	1.0	10	Fe	70	75	6.98
4	−1	−1	−1	0.2	2	Al	77	74	0.09
5	−1	+1	−1	0.2	10	Al	94	87	0.48
6	+1	+1	−1	1.0	10	Al	96	93	8.77
7	+1	−1	−1	1.0	2	Al	86	99	1.60
8	−1	+1	+1	0.2	10	Fe	27	62	0.38

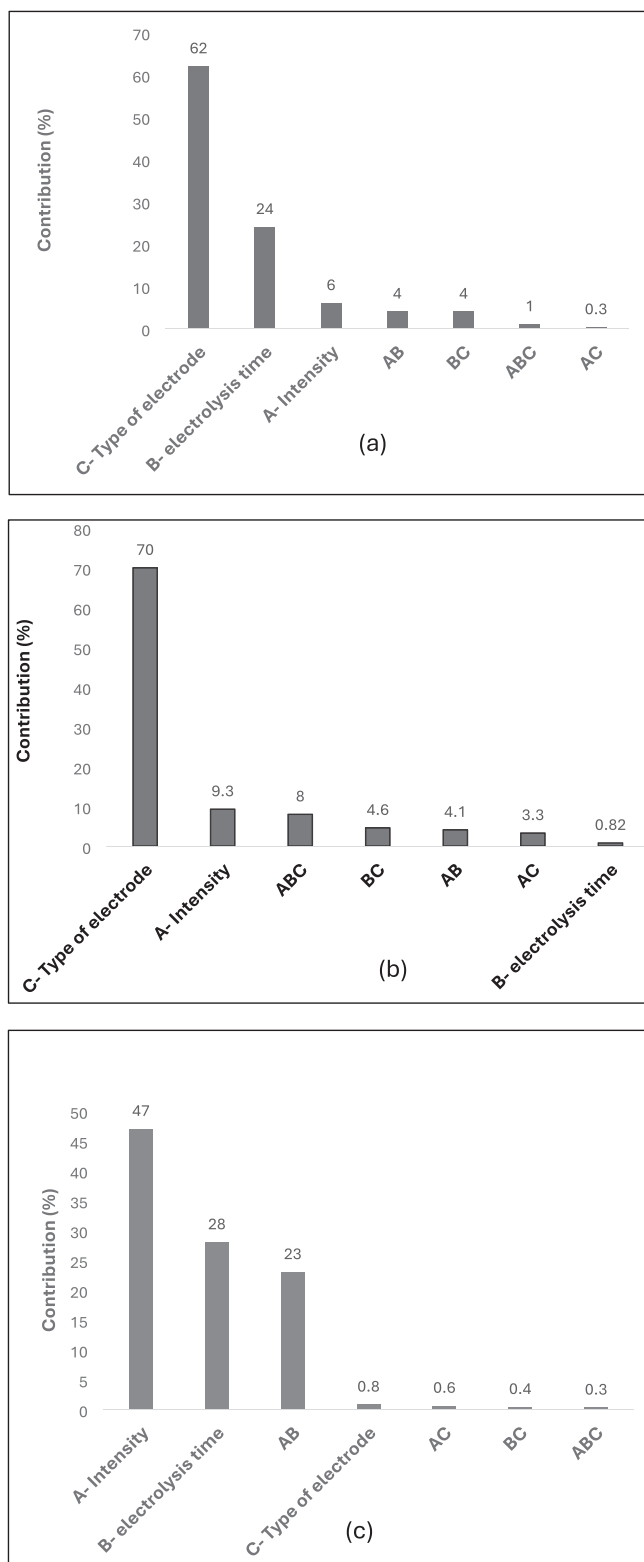


FIGURE 2 | Influence of EC operating variables on the removal of (a) TSS, (b) turbidity, and (c) energy consumption (Farm 1).

rounded box, represents the average turbidity removal achieved in experiments using this configuration (Assays 2 and 3).

When iron electrodes (the highest level of factor X_3) are used at a high current intensity of 1.0 A (factor X_1), the type of electrode clearly has a significant effect on turbidity removal. In this case,

the average removal rate increases from 40.5% to 62.0%, representing a gain of 21.5 percentage points. In contrast, when aluminum electrodes (the low level of X_3) are used, increasing the current intensity from 0.5 to 1.0 A results in a more modest improvement—from 85.5% to 91%, a difference of only 5.5 points. These results indicate that the effect of current intensity is not uniform across all conditions; rather, it is influenced by the electrode material. In other words, the impact of one factor (current intensity) depends on the level of another (electrode type), highlighting a significant interaction between the two.

3.3 | Optimization Conditions for VWW Treatment Using CCD Methodology

3.3.1 | Optimization Conditions for TSS and Turbidity Removal Using CCD for the Treatment of VWW Coming From Farm 1

Results of CCD experiments are presented in Table 5. For TSS removal, the coefficients of the model (linear model) were calculated using the Design-Expert program software.

$$\text{For the Al anode electrode: } Y_2 = 23.33 + 63.58X_1 + 7.06X_2 \quad (10)$$

$$\text{For the Fe anode electrode: } Y_2 = 53.56 + 41.99X_1 + 3.95X_2 \quad (11)$$

Regardless of the electrode type (aluminum or iron), Equations (10) and (11) indicate that both current intensity and treatment time play a significant role in TSS removal. These two factors have a positive effect on the response: Increasing either the treatment time or the current intensity leads to improved TSS removal. Their impact is more pronounced when using aluminum electrodes compared to iron ones. As illustrated in Figure 5, the percentage of TSS removal increases with both current intensity and treatment time. Maximum removal is observed within the current intensity range of 0.32 to 0.88 A and treatment time between 3.17 and 8.8 min. Figure 6 presents a comparison between the actual TSS removal values measured during the experiments and the values predicted by the Design-Expert software. The close agreement between experimental and predicted results confirms the reliability of the model.

To determine the optimal condition for TSS removal in terms of cost and effectiveness, energy consumption during EC must be considered. To save treatment costs, electrolysis time and current intensity must be kept to a minimum, whereas the TSS removal rate must be maximized. The treatment costs include energy and electrolyte costs (if needed). Based on these defined criteria, Design-Expert software generated optimal solutions, identifying one suitable condition for each type of anode material (Table 6).

The removal efficiencies for turbidity, COD, TP, and selected pesticides were assessed under the optimal (EC) conditions for treating wastewater from Farm 1 (VWW). Under these conditions, EC achieved removal rates of 98.4% for turbidity removal, 45% for COD, and 93% for TP, demonstrating its high

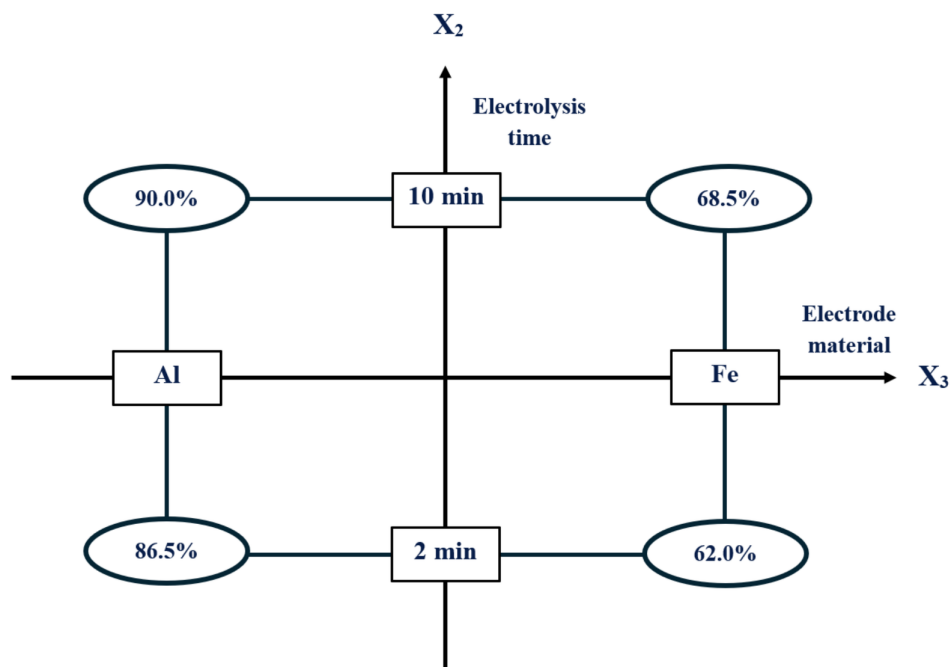


FIGURE 3 | Interaction between type of electrode material (X_3) and electrolysis time (X_2) on TSS removal.

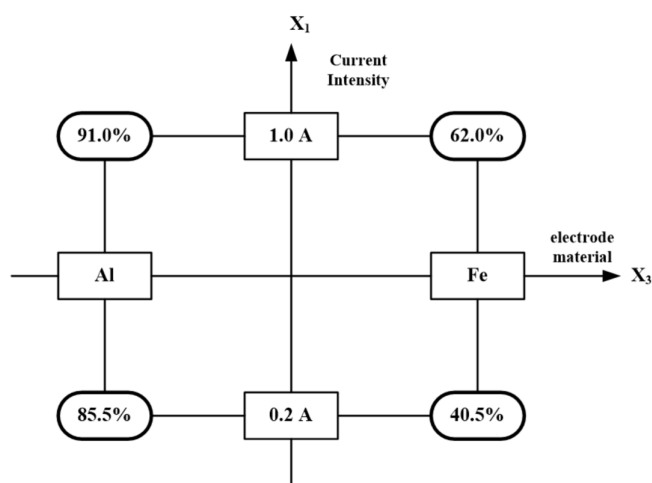


FIGURE 4 | Turbidity removal: interaction b_{13} between type of electrode material (X_3) and current intensity (X_1).

effectiveness for phosphorus elimination. This performance can be attributed to the ability of EC to destabilize and aggregate phosphorus-containing particles, which are then removed through precipitation or adsorption mechanisms (Nguyen et al. 2016; Sanni 2018). Among all raw samples analyzed in this study, those from Farm 1 exhibited pesticide concentrations exceeding regulatory limits. EC treatment effectively reduced the concentrations of neonicotinoid insecticides, with TMX decreasing from 0.71 to 0.44 $\mu\text{g/L}$ and CLO increasing slightly from 0.25 to 0.76 $\mu\text{g/L}$. However, despite these reductions, the final concentrations remained significantly above the discharge limit set by MELCCFP, which is 0.0083 $\mu\text{g/L}$.

The relatively reduced efficacy of EC in eliminating specific dissolved organic chemicals and pesticides, including TMX, can be ascribed to the inherent physicochemical mechanisms

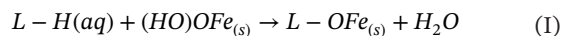
of the process. In contrast to advanced oxidation methods, EC principally depends on the in situ generation of metal hydroxides through the anodic dissolution of iron or aluminum, which function as coagulants via adsorption, complexation, or entrapment inside the flocs (Biswas and Goel 2022; Ganiyu et al. 2018). These interactions work best for chemicals that are hydrophobic or have weak polar properties. They do not work as well for molecules highly hydrophobic and do not absorb easily, like TMX and its principal transformation product, CLO. TMX has a very polar chemical structure. This is because it has a heterocycle with a nitroguanidine group, which makes it very soluble in water and not very attracted to the surfaces of metal hydroxides. Because it does not adsorb easily, it cannot be removed by coagulation or sorption. Additionally, a fraction of TMX experiences partial transformation because of locally generated oxidizing species in the EC reactor, particularly hydroxyl radicals, resulting in the enhanced production of CLO, a more stable and enduring by-product (Sant  Canada 2018). So, although TMX is partially changed, EC does not completely mineralize it (into CO_2 , H_2O , and NH_3). Instead, it changes a parent pesticide into a secondary metabolite that is harder to break down. Under typical EC conditions, oxidation is usually limited, and the transformation of TMX to CLO via hydroxyl radicals may not be dominant. It might be helpful to consider that the removal of TMX and CLO could also be largely related to their association with suspended solids and removal through coagulation/flocculation mechanisms.

- It is worth noting that, at the start of EC experiments, aluminum or ferrous ions were respectively produced by anodic dissolution, which reacted immediately with hydroxide ions in solution to produce $\text{Al}(\text{OH})_3$ and $\text{Fe}(\text{OH})_2$. Metallic hydroxide particles were produced up to a sufficient concentration to initiate polymerization reactions, inducing the formation of a green precipitate and white

TABLE 5 | Central composite matrix and experimental results.

Tests	Experimental design		Experimental plan		Experimental responses		
	X_1	X_2	U_1 (A)	U_2 (min)	Turbidity removal (%)	TSS removal (%)	Energy consumption (kWh/m ³)
Al electrode (U_3)							
9	−1.41	0	0.32	6.00	61	64	0.23
10	1.41	0	0.88	6.00	92	92	4.00
11	0	−1.41	0.60	3.17	61	67	0.45
12	0	1.41	0.60	8.80	94	92	3.44
13	0	0	0.60	6.00	90	88	1.78
14	0	0	0.60	6.00	91	89	1.89
15	0	0	0.60	6.00	91	90	1.92
16	0	0	0.60	6.00	90	90	1.85
17	0	0	0.60	6.00	89	88	1.68
Fe electrode (U_3)							
18	−1.41	0	0.32	6.00	46	68	0.19
19	1.41	0	0.88	6.00	51	73	3.78
20	0	−1.41	0.60	3.17	50	80	0.33
21	0	1.41	0.60	8.80	66	82	2.78
22	0	0	0.60	6.00	60	80	1.44
23	0	0	0.60	6.00	41	74	1.67
24	0	0	0.60	6.00	43	81	1.56
25	0	0	0.60	6.00	58	66	1.50
26	0	0	0.60	6.00	58	72	1.46

gelatinous precipitate using mild steel and aluminum electrodes, respectively. The dissolved organic compounds (such as pesticides) can be removed by surface complexation or electrostatic attraction with the polymeric metal complexes (Ibanez et al. 1998; Laridi et al. 2005; Rajeshwar and Ibanez 1997). The equation mentioned below illustrates the surface complexation in which the dissolved pollutant can act as a ligand (L) to bind a hydrous iron moiety (Laridi et al. 2005):



- In electrostatic attraction, the polymeric iron or aluminum complexes can have both positive and negative charge capable of attracting the opposite charge of polluting species and removing them from solution (Ibanez et al. 1998).

These findings support what we know about how EC works on soluble organic pollutants: Coagulation mechanisms are more common than oxidation events, which stops total molecular breakdown. To make this type of compound work better,

we could use a combination of EC and an advanced oxidation process (like electro-Fenton or photo-EC) that can make more hydroxyl radicals. This would help break down TMX and CLO faster (Biswas and Goel 2022; Halkijevic et al. 2024). The EC cost treatment for *Farm 1* is CAD\$1.41/m³. This includes electrode consumption, energy consumption, and sludge disposal.

3.3.2 | Application to the Treatment of Other VWW Under the Optimal Conditions Previously Determined

The optimal conditions determined while treating VWW from *Farm 1* were then applied for the treatment of VWWs from *Farm 2* (white potatoes), *Farm 3* (leeks), and *Farm 4* (red beets). The results summarized in Table 7 compare the untreated effluent (raw water) with electrocoagulated-settled effluent. In addition, to facilitate comparison across farms, selected key parameters (TSS, turbidity, and P_p), before and after EC optimization, have been illustrated, respectively, in Figures 7 and 8. The analyses were carried out in the supernatant after settling.

Factor Coding: Actual

TSS removal (%)

Design Points:

● Above Surface

○ Below Surface

57  92

X1 = A

X2 = B

Actual Factor

C = Aluminium

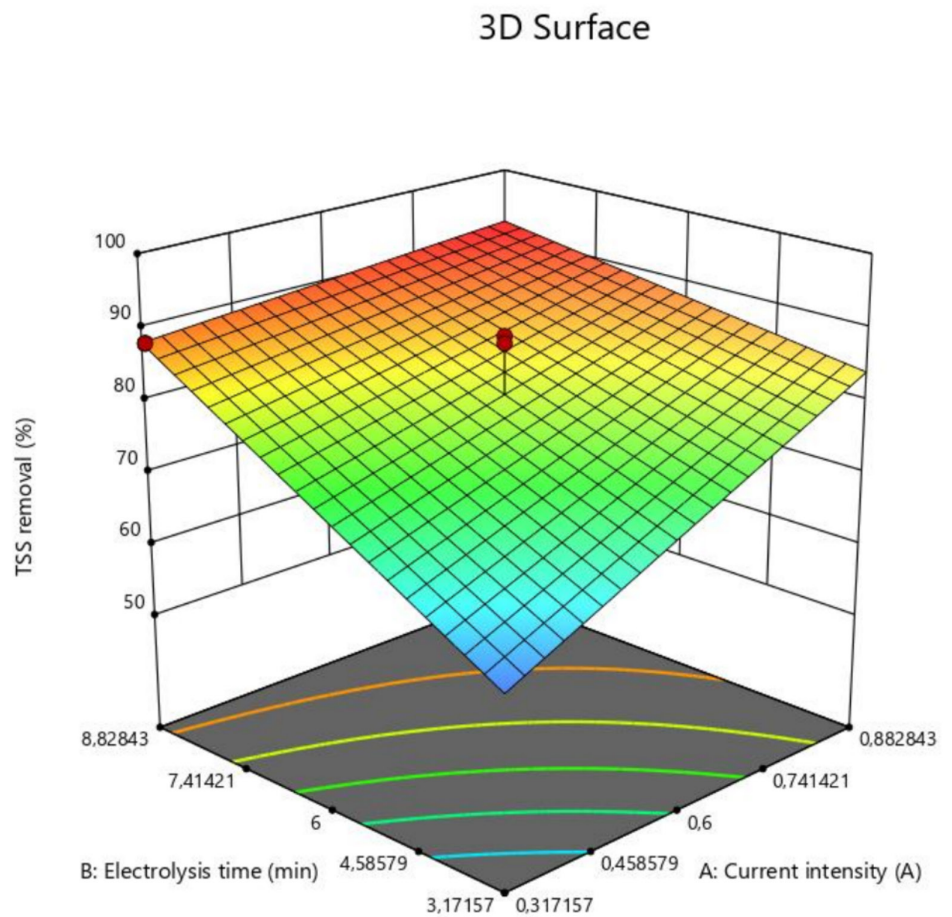


FIGURE 5 | Effect of current intensity (A) and electrolysis time (B) on the TSS removal, using aluminum electrodes ($C = X_3$).

TSS removal

Color points by value of
TSS removal:

62  93

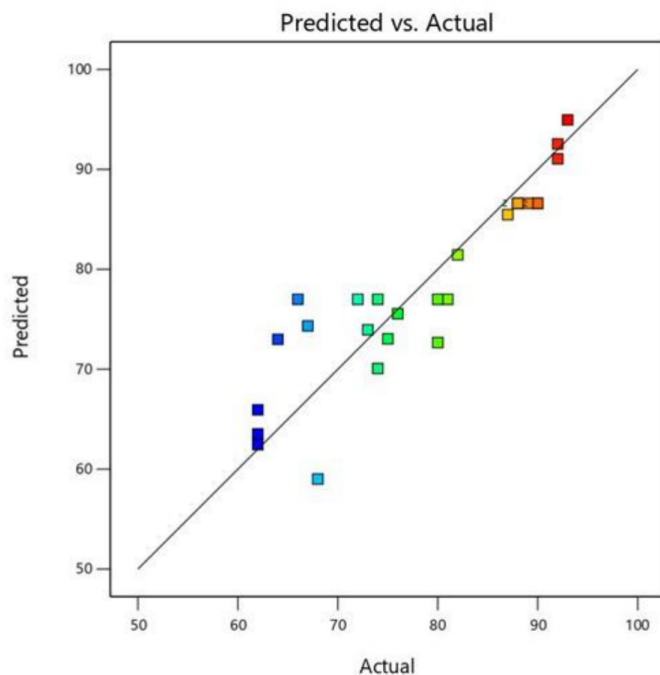


FIGURE 6 | Comparison between experimental and predicted values for removal of TSS.

- Treatment of white potatoes VWW (Farm 2): Turbidity, total solids, and suspended solids decreased by over 90%. The TSS concentration (20 ± 2 mg/L) was below the

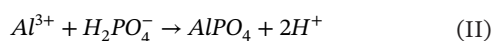
discharge limit of 50 mg/L (Figure 8). Pesticides have not been identified in *Farm 2* samples before and after EC. The treatment cost (including electrode consumption, energy

TABLE 6 | Optimal conditions proposed by Design-Expert program software (predicted and experimental responses).

Tests	Factors			Predicted responses		Experimental responses	
				TSS removal	Energy consumption	TSS removal	Energy consumption
	U_1	U_2	U_3	(%)	(kWh/m ³)	(%)	(kWh/m ³)
1	0.32 A	8.8 min	Al	88	1	98	1
2	0.80 A	8.8 min	Fe	76	5	80	5

consumption, and sludge disposal) using EC optimal conditions (Al electrode, 0.32 A and 8.8 min for electrolysis time) was CAD\$0.96/m³.

- Treatment of leeks VWW (Farm 3): EC treatment of leek VWW reduced turbidity by 98% and suspended solids by 99%. Conversely, CLO (0.1 µg/L) and TMX (0.002 µg/L) were entirely removed by EC. The TSS concentration of 8 mg/L is well below the discharge limit of 50 mg/L. Additionally, a significant decrease in COD to 27 ± 2 mg/L was observed. The initial value was 97 ± 15 mg/L. Following EC, removal rates exceeding 99% were observed for the pesticides present in raw leek washwater. The metal hydroxides generated during the process such as Al(OH)₃ likely contribute to this removal by neutralizing the charges of pesticide molecules and adsorbing them onto the flocs formed in the treated effluent (Ammar et al. 2023). EC treatment cost is CAD\$1.83/m³.
- Treatment of red beets VWW (Farm 4): Table 7 and Figure 7 show that the raw water from red beet washing contained the highest initial turbidity (2467 ± 114 NTU), TSS (1957 ± 398 mg/L), COD (479 ± 82 mg/L), and P_t (4.2 ± 0.3 mg/L) concentrations. CLO and TMX concentrations were both below 0.002 µg/L, which complied with the neonicotinoid's permissive level of 0.0083 µg/L. The application of EC followed by sedimentation allowed 88% removal of turbidity, 82% of TSS, and 75% COD. Turbidity and TSSs were effectively removed from the electrocoagulated effluent primarily through charge neutralization by Al³⁺ ions generated during electrolysis, followed by the agglomeration of destabilized particles that were subsequently separated by sedimentation. The reduction in COD can be attributed to the sedimentation of organic matter present as suspended solids or colloidal particles (Asselin et al. 2008; Sanni et al. 2022). Notably, after EC and sedimentation, the residual turbidity (P_r) concentration decreased to 0.02 ± 0.01 mg/L, compared to an initial value of 4.2 ± 0.3 mg/L in the raw water, representing a removal efficiency of over 99%. This significant dephosphatation is the result of phosphate precipitation with Al³⁺ ions produced via anodic dissolution, as described in Equation (II).



Under optimal conditions, EC removed the true color of the sample, decreasing from 283 to 60 UCV, a 79% reduction. True color corresponds to the color of a water sample once turbidity has been eliminated (CEAEQ 2023). Despite this significant improvement, a persistent red tint remained visible in the treated effluent. This residual color highlights both the strength and the limitations of

EC when dealing with highly chromophoric natural compounds such as betanin, the main pigment responsible for the red color of beets. Betalains, primarily betanin, are water-soluble nitrogen-containing pigments characterized by high chemical stability under slightly acidic or neutral conditions, the same pH range commonly used in EC operations (Abedi-Firoozjah et al. 2023; Daghrir et al. 2012). Although EC effectively destabilizes colloidal and particulate species by charge neutralization and hydroxide floc formation, it is less effective against soluble organic matter that does not adsorb strongly to Al(OH)₃ flocs or that resists oxidation. The amount of aluminum hydroxide generated may be sufficient to remove suspended solids and part of the colloidal organic matter but insufficient to fully encapsulate or adsorb the dissolved betalains. Thus, the residual color likely corresponds to fractions of soluble pigments that remain in suspension even after coagulation.

Achieving complete color removal may necessitate a hybrid or sequential treatment strategy, wherein EC is employed as a primary step for effective solid-liquid separation and substantial color reduction, followed by an oxidative or adsorptive process such as electrooxidation (EO), activated carbon adsorption, or biological treatment, specifically tailored to the degradation of residual soluble pigments.

The coloration of water can be of natural origins (metallic elements, humic matter, etc.) or associated with its pollution (colored organic compounds synonymous with the presence of dissolved compounds). As explained above (Section 3.3.1), dissolved organic compounds can be removed by surface complexation or electrostatic attraction with the polymeric metal complexes (green precipitate and white gelatinous precipitate, respectively). For Farm 4, the cost of treatment was CAD\$5.66/m³.

Application of EC under optimized operating conditions achieved over 95% removal of Al³⁺ ions across the four farms investigated (Table 7). Although EC with aluminum electrodes inherently generates dissolved Al³⁺ in the treated effluent, these high removal efficiencies indicate that most of the electrochemically released aluminum was effectively incorporated into settleable flocs or removed during subsequent solid-liquid separation, leaving a negligible residual concentration of Al³⁺ in solution (0.06–0.8 mg/L). This behavior is consistent with previous studies showing that aluminum-based EC and coagulation processes efficiently capture dissolved and colloidal aluminum species in the solid phase, even though a residual fraction of aluminum typically remains in the treated water because of speciation dynamics and incomplete floc separation. The extent of this residual is governed by solution pH, which controls aluminum speciation: At pH values between 6 and 8, Al³⁺ predominantly precipitates as

TABLE 7 | Electrocoagulation tests during treatment of different vegetable washwaters (VWWs) while imposing the best conditions (current intensity = 0.32 A; electrolysis time = 8.8 min; and settling time = 60 min).

Parameters	Red potatoes VWW (Farm 1)		White potatoes VWW (Farm 2)		Leeks VWW (Farm 3)		Red beet VWW (Farm 4)	
	Raw eff.	Electrocoagulated settled effluent	Raw eff.	Electrocoagulated settled effluent	Raw eff.	Electrocoagulated settled effluent	Raw eff.	Electrocoagulated settled effluent
pH	7.2 ± 0.4	6.5 ± 0.3	7.1 ± 0.2	6.8 ± 0.3	6.5 ± 0.2	7.5 ± 0.3	7.5 ± 0.2	8.4 ± 0.1
Turbidity (NTU)	246 ± 21	3.8 ± 0.1	468 ± 35	8.2 ± 0.3	1105 ± 78	22 ± 4	2467 ± 114	285 ± 4
Turbidity removal (%)	—	98 ± 0.1	—	98 ± 0.1	—	98 ± 0.3	—	88 ± 0.7
TSS (mg/L)	215 ± 41	1.6 ± 0.7	495 ± 154	20 ± 2	2193 ± 154	8.0 ± 1.0	1957 ± 398	357 ± 29
TSS removal (%)	—	99 ± 0.3	—	96 ± 0.4	—	99 ± 0.0	—	82 ± 5
COD (mg/L)	145 ± 32	80 ± 2.3	83 ± 13	22 ± 3	97 ± 15	27 ± 2	479 ± 82	118 ± 66
COD removal (%)	—	43 ± 11	—	74 ± 3	—	72 ± 4	—	75 ± 18
True color (UCV)	—	—	—	—	—	—	283 ± 27	60 ± 5
True color removal (%)	—	—	—	—	—	—	—	75 ± 6
P_i (mg/L)	1.4 ± 0.4	0.1 ± 0.04	14 ± 0.2	4.4 ± 0.9	< 0.55	< 0.55	4.2 ± 0.3	0.02 ± 0.01
P_i removal (%)	—	90 ± 4	—	68 ± 7	—	—	—	99 ± 0.0
Al ³⁺ (mg/L)	13.2 ± 1.6	0.06 ± 0.02	3.5 ± 0.3	0.8 ± 0.3	12 ± 0.5	0.5 ± 0.04	23 ± 2	0.4 ± 0.1
Al ³⁺ removal (%)	—	99.5 ± 0.1	—	78 ± 9	—	96 ± 0.4	—	99.4 ± 0.6
Fe ³⁺ (mg/L)	2.2 ± 0.2	0.06 ± 0.02	3.4 ± 0.3	2.2 ± 0.9	14 ± 4	0.05 ± 0.02	37 ± 1	0.04 ± 0.01
Fe ³⁺ removal (%)	—	98.9 ± 0.4	—	39 ± 25	—	99.5 ± 0.2	—	99.9 ± 0.03
TMX (µg/L)	0.71 ± 0.01	0.44 ± 0.01	—	—	0.02 ± 0.01	0.0 ± 0.0	< 0.002	< 0.002
TMX removal (%)	—	38 ± 2	—	—	—	100 ± 0.0	—	—
CLO (µg/L)	0.25 ± 0.01	0.76 ± 0.01	—	—	0.1 ± 0.01	0.0 ± 0.0	< 0.002	< 0.002
CLO removal (%)	—	—	—	—	—	100 ± 0.0	—	—

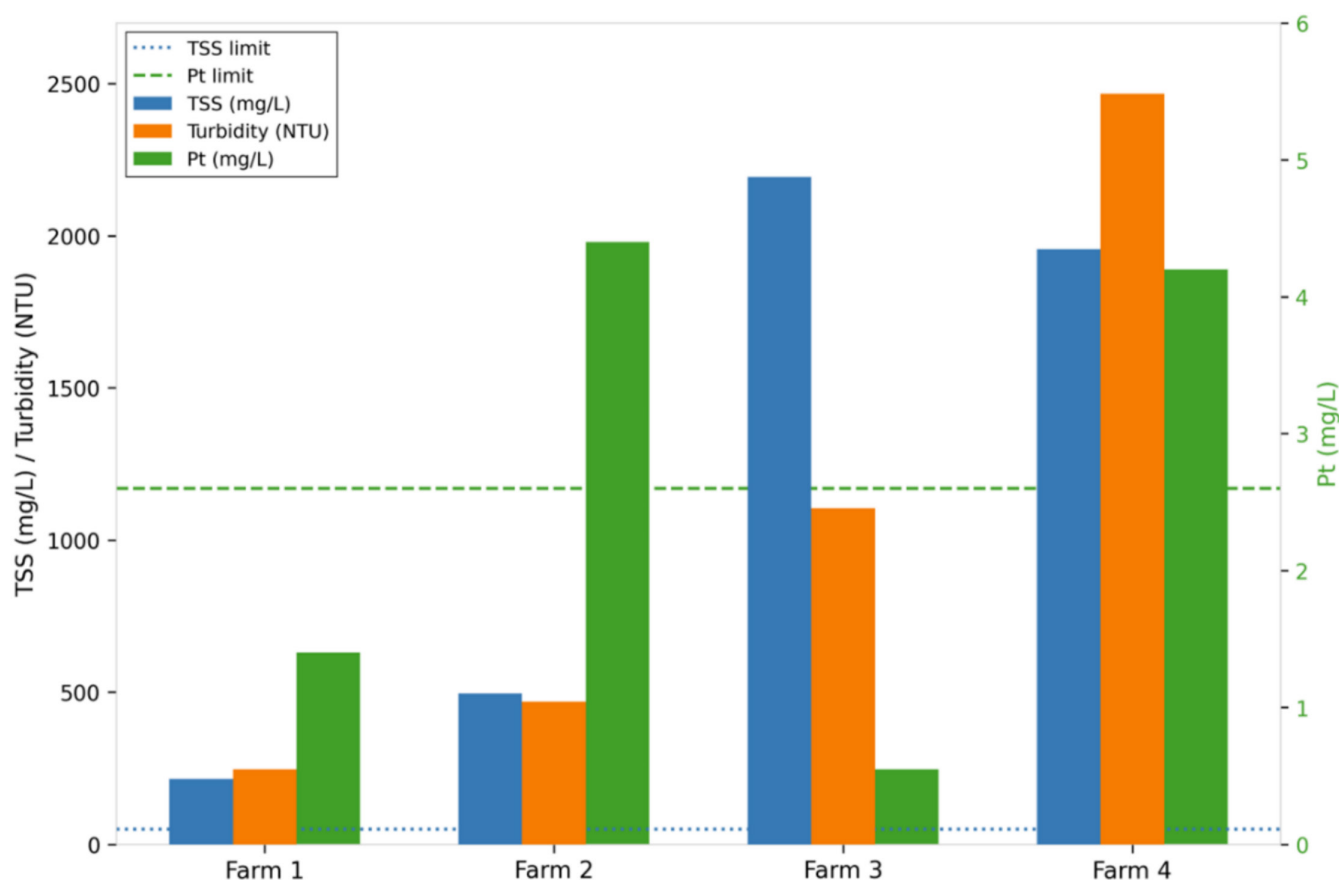


FIGURE 7 | Initial water quality parameters (TSS, turbidity, and P_t) in vegetable washwater before electrocoagulation optimization: comparison with discharge limits.

$\text{Al}(\text{OH})_3$, minimizing dissolved residuals, whereas lower or higher pH values favor soluble aluminum species (Guvenc et al. 2017; Krupińska 2020). Residual Al^{3+} concentrations (0.06–0.8 mg/L) remained well below the Canadian maximum acceptable concentration (MAC) of 2.9 mg/L for total aluminum in drinking water (Sant  Canada 2021). However, they may approach or exceed the more stringent operational guideline range of 0.1–0.2 mg/L recommended by Health Canada, WHO, and the USEPA, which primarily targets treatment performance and distribution system stability rather than direct health protection (Sant  Canada 2021; Water Quality Association 2013). Given that the treated vegetable washing waters are not intended for direct human consumption, the MAC constitutes the most relevant health-based benchmark.

In addition to pollutant removal, the water recovery rate was assessed as an indicator of process efficiency. The initial volume treated by EC was 500 mL, whereas 400 mL of clarified effluent was recovered after treatment, corresponding to a recovery rate of 80%. Although this recovery rate indicates some water loss (20%), mainly attributable to sludge production, electrode dissolution, and operational losses, it remains acceptable for complex effluents such as VWW, especially considering that EC is commonly reported to generate limited sludge volumes and enable clarification of highly loaded industrial and agro-industrial effluents without excessive water loss (Uludag-Demirer et al. 2020). In this study by Uludag-Demirer

et al. (2020), EC has also been shown, in the context of a technico-economic analysis on anaerobic digestion effluent, to significantly reduce bacterial and viral indicators while maintaining a treatment cost compatible with water reuse scenarios, thereby reinforcing its relevance for applications where both contaminant abatement and safe effluent valorization are targeted. They found an 84%–90% water recovery rate after applying EC. From this perspective, the 80% water recovery obtained in the present study appears consistent with the performance envelopes reported for EC when designed for water recycling, where high removal efficiencies are sought without compromising the volume available for reuse, for instance, as process water, washing water, or irrigation supply.

To the best of our knowledge, the decontamination of VWWs by the EC process has not yet been sufficiently explored. Only the study conducted in Ontario has evaluated the feasibility of EC for the treatment of VWW (Zytner and Warriner 2016). However, this study did not explore the capacity of EC for removing simultaneously insoluble and soluble pollutants (such as turbidity, color, TMX, and CLO). Because of EC, TSS and COD showed removal rates over 80% in the VWW studied in Ontario. The current study achieved reductions exceeding 93% in TSS, turbidity, and TP (Farms 1 and 3). Furthermore, a complete removal of neonicotinoid insecticides was obtained in Farm 3. The initial concentrations were 0.02 $\mu\text{g/L}$ for TMX and 0.1 $\mu\text{g/L}$ for CLO.

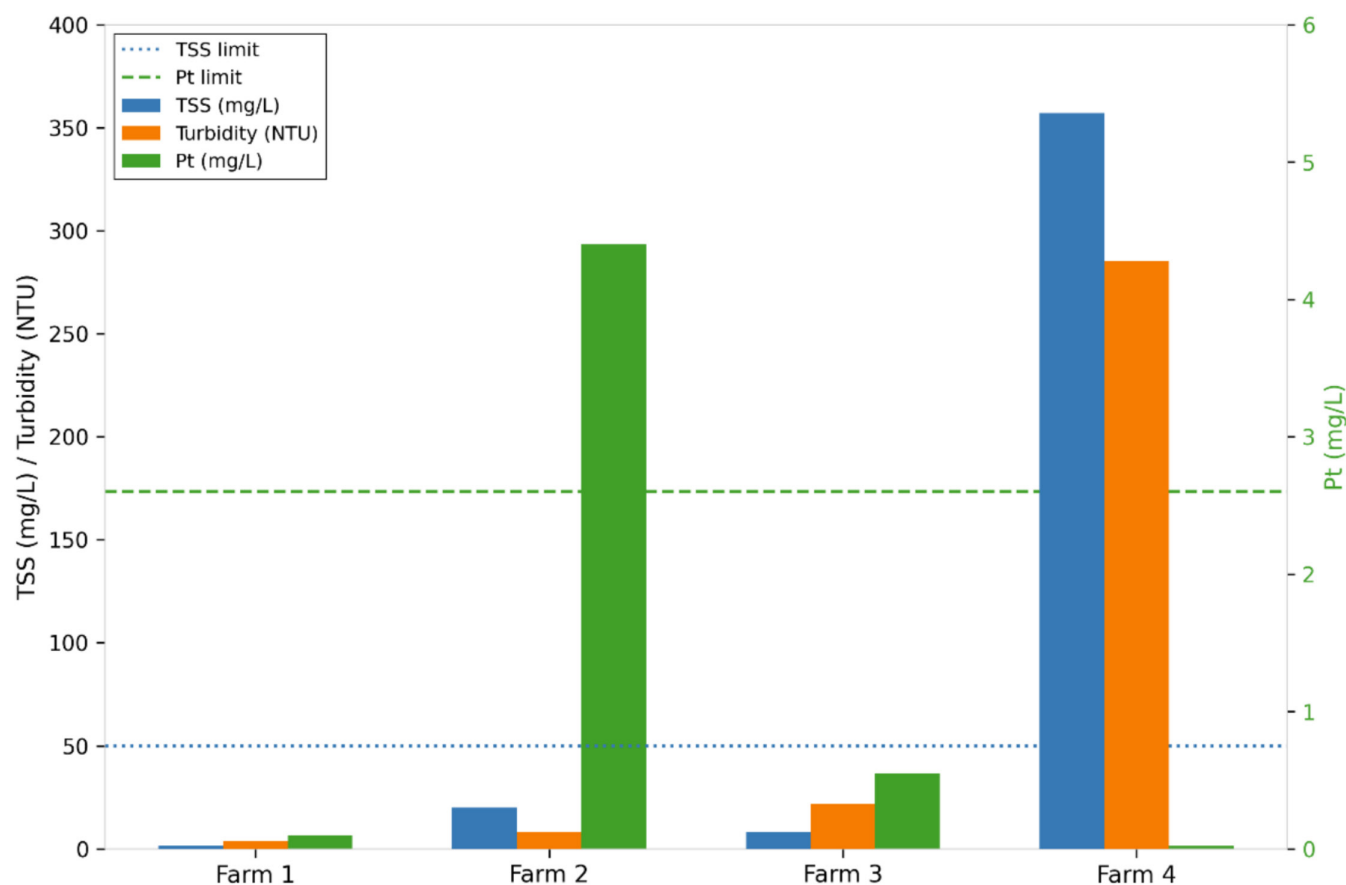


FIGURE 8 | Residual levels of TSS, turbidity, and P_t in vegetable washwater after optimized electrocoagulation treatment: comparison with discharge limits.

3.3.3 | Economic Analysis of VWW EC Treatment Under Optimal Conditions

According to our estimates, the operational costs associated with clarifying VWW via EC (accounting for energy consumption, sludge management, and electrode consumption) range from CAD\$0.96/m³ to CAD\$5.66/m³. These values position EC as a competitive treatment option, particularly when costs remain below CAD\$2/m³ (as observed in *Farms 1* and *2*), which is comparable to conventional chemical processes and considerably lower than biological treatment methods. Lehto et al. (2009) reported that sequential bioreactor treatment can reach investment and operating costs of, respectively, approximately €5000/m³ (almost equal to CAD\$7558) and €2/m³ (almost equal to CAD\$3.24), whereas biofilters and chemical precipitation incur relatively lower costs (€2500/m³/day and €0.3/m³/day, respectively). Furthermore, the installation of traditional treatment filters such as grit chambers, sedimentation basins, and lagoons is estimated at around CAD\$20,000 in Quebec, with annual maintenance expenses near CAD\$1000 (Brassard et al. 2014). In this context, notwithstanding the dependence on initial effluent quality and operational conditions, EC emerges as a viable alternative for producers, as it couples high efficacy in water clarification with more affordable operational costs. Therefore, although our cost estimates do not consider initial capital investment or equipment maintenance, they underscore the potential of EC as a financially feasible strategy for managing VWW water.

4 | Conclusions

Suspended solids represent a major challenge in the treatment of washwater from root vegetables. In this study, RSM was applied to optimize the EC conditions for this sample of wastewater. Optimal results were achieved using a current intensity of 0.32 A, a treatment time of 8.8 min, and aluminum electrodes, leading to significant reductions in suspended solids, total solids, and turbidity. After EC treatment, the concentrations of suspended solids in effluents from sandy loam, white potatoes on loamy sand, and leeks on clay loam were brought below the 50 mg/L discharge threshold set by the Quebec Ministry of the Environment. Although EC proved effective in removing solids and adsorbed pollutants, it showed limited efficiency in mineralizing dissolved organic compounds. Under the optimal conditions of EC treatment, the removal rate of COD ranged between 45 ± 11% and 75 ± 18%. For initial concentrations less than or equal to 0.1 µg/L, a 100% removal of TMX and CLO was observed. However, TMX neonicotinoid insecticide removal by EC was 38 ± 2% when TMX concentration before EC was higher than 0.1 µg/L, which is 0.71 µg/L. To address this limitation, particularly for the degradation of pesticides and other persistent organic contaminants, EO could be considered as a complementary treatment. Additionally, to eliminate the red coloration in beet washwater, further studies should focus on identifying the optimal parameters for EC or EO treatments. Finally, the differences in treatment costs by EC observed from one farm to

another (CAD\$0.96–5.66/m³) reveal that the specific characteristics of each effluent must be considered prior to applying EC.

Author Contributions

Ablema Sephora Tanoe: conceptualization, investigation, writing – original draft, methodology, visualization, writing – review and editing, software, formal analysis, data curation. **Patrick Drogui:** conceptualization, funding acquisition, methodology, validation, software, data curation, supervision, writing – review and editing, project administration, resources. **Mahdieh Khajvand:** writing – review and editing. **Joahnn Palacios:** writing – review and editing, project administration. **Julien G. Mahy:** visualization, writing – review and editing. **Adama Ndao:** writing – review and editing. **Kokou Adjallé:** writing – review and editing. **Stéphane Godbout:** supervision, writing – review and editing, project administration.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All relevant data are included in the paper.

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