

Sustainable copper recovery from industrial effluents through iron screen-assisted cementation under stirred conditions

Mohamed Abbas El-Naggar^{1,2} 

¹ Department of General Subjects, University of Business and Technology, Jeddah 21361, Saudi Arabia

² Chemical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria 21544, Egypt
E-mail: m.abbas.elnaggar@alexu.edu.eg

ABSTRACT

This study introduces a cementation system employing iron screens positioned within a mechanically stirred batch reactor for efficient copper extraction from wastewater. Systematic experimental investigations examined the influence of four operational parameters: initial copper concentration (0.01–0.03 M), agitation speed (100–800 rpm), reaction duration (up to 50 minutes), and number of iron screens (3–7). Results demonstrated that copper removal efficiency reached 82–88% under optimized conditions, with the process governed primarily by external mass transfer rather than surface reaction kinetics. Response Surface Methodology yielded a highly predictive quadratic model with good agreement between experimental and predicted values of copper removal ($R^2 = 0.9846$). Multi-objective optimization identified optimal operating parameters: 0.0295 M initial concentration, 757 rpm agitation intensity, 47.4 minutes reaction time, and three iron screens, achieving 87.57% copper recovery. The proposed system offers distinct advantages including operational simplicity, direct recovery of metallic copper, minimal chemical consumption, and straightforward industrial scalability. This work presents a sustainable, cost-effective solution for copper-bearing wastewater treatment that simultaneously addresses environmental protection and resource recovery imperatives.

Keywords: copper recovery, cementation, wastewater treatment, response surface methodology, mass transfer, agitated vessels.

INTRODUCTION

Environmental pollution has emerged as one of the most critical global challenges of the 21st century, with industrial effluents contributing significantly to water contamination worldwide. Heavy metal pollution poses severe threats to aquatic ecosystems and human health due to the non-biodegradable nature and bioaccumulative properties of these contaminants (Wang et al., 2022). Among various industrial pollutants, heavy metals such as copper have attracted considerable attention due to their persistence in the environment and potential carcinogenic effects even at trace concentrations (Liu et al., 2023). Copper contamination in industrial wastewater originates from numerous sources including metal plating facilities, mining operations, electronic manufacturing, and electroplating industries (Ab Hamid et al., 2022). Copper

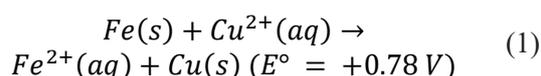
concentrations in industrial wastewater typically range from 2.5 mg/L to 10,000 mg/L, significantly exceeding permissible discharge limits (WHO: 2–3 mg/L; EPA: 1.3 mg/L) (Liu et al., 2023). Excessive copper in aquatic environments exhibits acute toxicity to aquatic organisms and causes gastrointestinal disorders, liver cirrhosis, kidney dysfunction, and neurological damage in humans (Liu et al., 2023; Yan et al., 2022). Beyond environmental protection, copper recovery presents substantial economic incentives, as wastewater streams become valuable secondary resources aligning with circular economy principles (Gowayed et al., 2025; Li et al., 2024).

Numerous technologies have been developed for copper removal from industrial wastewater. Table 1 summarizes the most common reported techniques for copper removal with their merits and drawbacks. Among copper recovery technologies,

Table 1. The most common reported techniques for copper removal with their merits and drawbacks

Technique	Merits (Advantages)	Drawbacks (Limitations)
Chemical precipitation	Simple and cost-effective.	Generates substantial toxic sludge; achieves incomplete metal removal at low concentrations [2, 5].
Ion exchange	High removal efficiency (>99%) [2].	High operational costs; sensitivity to competing ions [2, 7].
Adsorption (activated carbon, nanomaterials)	Versatile [8].	Regeneration remains challenging [8]; large-scale synthesis/regeneration challenges for nanomaterials [19].
Membrane filtration (advanced technologies)	Achieves excellent removal; ongoing development for improved fouling resistance [10, 20].	Suffers from fouling and high energy consumption [9, 10]; scale-up barriers [2, 3].
Electrochemical methods	Enables direct copper recovery.	Requires significant electrical energy; only viable for high-concentration streams [2].
Cementation (general)	Simple, no external energy required; direct recovery of high-purity metallic copper (up to 99%); applicable across wide concentration ranges; minimal chemical consumption [11, 12].	Traditional Designs: Particle agglomeration, difficult separation, rapid metal consumption, passivating surface layers, limited mass transfer rates [13, 14].
Enhanced cementation (e.g., using organic additives)	Demonstrates improved recovery efficiency (up to 47.6% improvement) [12].	Requires additional chemicals/additives; scale-up challenges [2, 3].
Innovative cementation (stirred tank reactor with iron screens)	Eliminates diffusion limitations via continuous stirring; hydrodynamic shear prevents passivating layers; easy installation/replacement of screens; modular design allows linear scale-up; reduced residence time (by 60–80% compared to conventional reactors) [12, 15-17].	Operational expenses include iron screen replacement and minimal stirring energy [5].
Nanomaterial-based adsorbents (e.g., Fe ₃ O ₄ nanorods)	Exceptional performance; high adsorption capacities (e.g., 76–127 mg/g) [18].	Faces challenges in large-scale synthesis and regeneration [19]; high costs and operational complexity [2, 3].

cementation represents an elegant electrochemical approach with distinct advantages. This process exploits the electrochemical series, wherein a more electronegative metal (such as iron) spontaneously reduces copper ions, depositing metallic copper:



This offers simplicity without external energy requirement, direct recovery of high-purity metallic copper (up to 99%), applicability across wide concentration ranges, and minimal chemical consumption (Al-Saydeh et al., 2017; Morsy et al., 2025). Traditional cementation using packed beds or iron powder encounters significant challenges including particle agglomeration, difficult separation, rapid metal consumption, passivating surface layers, and limited mass transfer rates (Amin and El-Ashtoukhy, 2011; Demirkiran et al., 2007).

The present research introduces a cementation configuration employing iron screens lining the inner wall of a stirred tank reactor, addressing fundamental limitations of previous designs. Continuous stirring ensures homogeneous mixing and eliminates diffusion limitations by maintaining high turbulence near the iron surface, dramatically accelerating copper deposition rates (Morsy

et al., 2025). Hydrodynamic shear forces continuously remove passivating layers and precipitated copper from screen surfaces, maintaining reactive iron exposure throughout operation (Gros et al., 2011). The screen configuration enables straightforward installation and replacement without process interruption, while the modular design allows linear scale-up, unlike packed beds which face severe channeling issues at industrial scale (Gros et al., 2008). Integration of mechanical agitation with cementation potentially reduces residence time by 60–80% compared to conventional reactors (Abdel-Aziz, 2011).

Economic feasibility depends on copper concentration, wastewater volume, recovery efficiency, and operational costs (Li et al., 2024). Copper recovery becomes economically attractive when influent concentrations exceed 50 mg/L (Gowayed et al., 2025). Additionally, compliance with environmental regulations adds hidden economic value by avoiding discharge penalties (Wang et al., 2022). Recent innovations in heavy metal recovery include nanomaterial-based adsorbents showing exceptional performance, with Fe₃O₄ nanorods exhibiting adsorption capacities of 76–127 mg/g for various metal ions (Karnwal and Malik, 2024), though facing challenges in large-scale synthesis

and regeneration (Ali et al., 2023). Advanced membrane technologies with improved fouling resistance continue evolving (Kapepula and Luis, 2024; Li et al., 2022), while enhanced cementation processes using organic additives demonstrate up to 47.6% improvement in copper recovery efficiency (Morsy et al., 2025). However, most emerging technologies encounter substantial barriers to industrial implementation including high costs, operational complexity, and scale-up challenges (Ab Hamid et al., 2022; Liu et al., 2023).

The iron screen cementation approach offers a pragmatic alternative, combining theoretical electrochemical principles with practical industrial applicability. Unlike nanomaterial systems requiring expensive synthesis and sophisticated regeneration, iron screens represent mature, readily available technology with straightforward replacement logistics. The cementation process tolerates wide operational parameter ranges while maintaining high efficiency, avoiding the energy intensity of electrochemical methods or the complexity of membrane systems. The simplicity of the iron screen-stirred tank configuration allows for easy integration of process enhancements such as organic accelerators (Morsy et al., 2025) or real-time monitoring systems. This research bridges the gap between fundamental electrochemical principles and practical industrial application, potentially offering a transformative solution for copper-bearing wastewater treatment that is simultaneously effective, economically viable, operationally simple, and environmentally sustainable, aligning with circular economy, resource recovery, and green chemistry principles that define modern environmental engineering practice.

In this study, response surface methodology (RSM) was employed to optimize the cementation process by relating copper recovery to key operating parameters and identifying the conditions that maximize performance within the investigated ranges. RSM is a statistical and mathematical technique used to quantify the effects of multiple variables, and derive empirical models that describe their combined influence on a response (Khuri and Mukhopadhyay, 2010)

Metallic copper recovery

After copper ions are removed from an aqueous solution by the cementation technique, metallic copper is recovered as a solid product deposited

on the surface of a more electropositive (sacrificial) metal, iron in the current work. The overall recovery of copper after cementation involves a sequence of physicochemical steps comprising precipitation, solid–liquid separation, washing, drying, and, if required, further purification.

During cementation, copper (II) ions (Cu^{2+}) in solution are reduced to metallic copper (Cu^0) through a redox displacement reaction, while the sacrificial metal undergoes oxidation. When iron is used as the cementing agent, the reaction proceeds according to Equation 1. The metallic copper formed typically appears as a finely divided solid that adheres to the surface of the iron or settles as a suspended precipitate. Once the cementation reaction reaches completion, the slurry containing solid copper and residual solution is subjected to solid – liquid separation. This is commonly can be achieved by filtration or sedimentation followed by decantation. The recovered copper precipitate is then thoroughly washed with deionized water to remove entrained electrolyte, soluble iron salts, and any remaining reactants. A dilute acid wash may be applied to dissolve surface oxides or residual cementing metal without significantly attacking the copper. After washing, the solid is dried under controlled conditions in an oven at moderate temperature, to remove moisture and obtain dry metallic copper.

MATERIALS AND METHODS

Materials

All chemicals employed in this study were of analytical reagent grade and used without further purification (Ayala and Fernández, 2014; Justel et al., 2020). Copper sulfate pentahydrate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, $\geq 99.0\%$ purity) served as the copper source for preparing synthetic aqueous solutions. Potassium iodide (KI, $\geq 99.0\%$), sodium thiosulfate pentahydrate ($\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$, $\geq 99.5\%$), soluble starch, glacial acetic acid (CH_3COOH), hydrochloric acid (HCl, 37%), and ammonium hydroxide (NH_4OH , 28–30%) were procured for analytical procedures. All aqueous solutions were prepared using double-distilled water (Wichers et al., 1953). Iron screens of commercial grade were utilized as the cementation substrate. Cementation is a well-established electrochemical process in which a less noble metal

(iron) reduces and precipitates a more noble metal ion (copper) from aqueous solution (Koseoglu et al., 2022; Stefanowicz et al., 1997). The large electrochemical potential difference between copper and iron ($\Delta E^\circ = 0.78$ V) ensures thermodynamically favorable and kinetically efficient copper recovery (Makhloufi et al., 2000). Prior to each experimental run, the iron screens were mechanically cleaned and pre-treated with dilute HCl solution (0.1 M) to remove surface oxides and contaminants, followed by thorough rinsing with distilled water and immediate use to prevent atmospheric oxidation (Shahrivar et al., 2020).

Apparatus

The cementation experiments in this study were conducted in a mechanically agitated batch reactor designed according to standard mixing vessel geometry to ensure hydrodynamic similarity and facilitate scale-up considerations (Paul et al., 2004). The reactor assembly comprised:

Figure 1 shows the set-up used in the present work. The apparatus consists of a transparent plexiglass cylindrical tank with an internal diameter (D) of 15 cm and height (H) of 25 cm, providing a working volume of 2.6 L. The transparent construction enabled visual observation of the cementation process and impeller performance.

Mechanical agitation was provided by a variable-speed digital motor coupled to a pitched-blade turbine impeller. The impeller featured

four blades arranged at 45° pitch angle, with blade height of 5 cm and width of 1 cm, positioned at standard off-bottom clearance. Pitched-blade turbines are particularly effective for solid-liquid contacting operations due to their high pumping capacity and axial flow characteristics (Armenante and Nagamine, 1998). The impeller shaft and blades were fabricated from stainless steel and subsequently coated with epoxy resin to ensure complete electrochemical isolation from the reactive medium, thereby preventing galvanic interactions that could interfere with the cementation kinetics (Mazumdar and Evans, 2009). Iron screens were deployed as the active cementation substrate, positioned strategically within the reactor to maximize contact with the copper-bearing solution while maintaining minimal interference with the fluid flow patterns established by the impeller.

Procedure

Batch cementation experiments were performed to investigate the effect of initial copper concentration on the removal kinetics and mass transfer characteristics. The cementation process is generally controlled by mass transfer of cupric ions from the bulk solution to the iron surface rather than by surface chemical reactions, particularly for systems with large electrochemical potential differences (Gros et al., 2008; Karavasteva, 2005). Each experimental

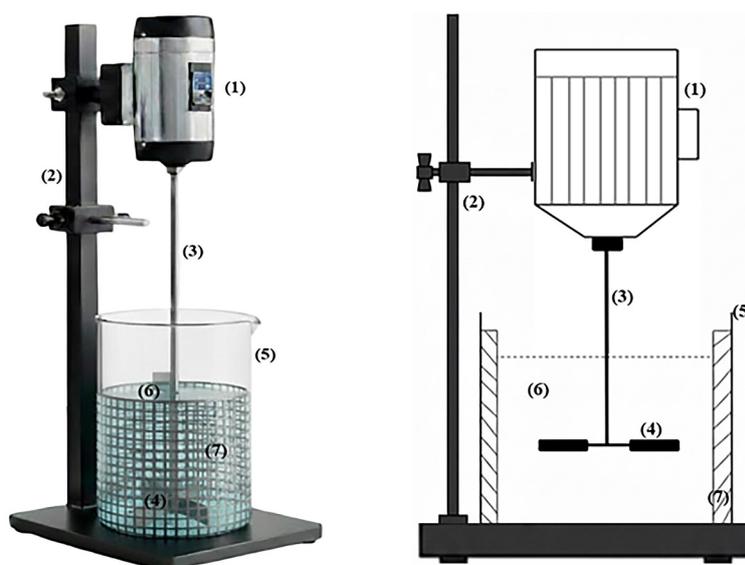


Figure 1. Schematic diagram of the batch cementation reactor system used in the experiments. (1) Digital Motor, (2) Support Stand, (3) Impeller Shaft, (4) Pitched Blade Impeller, (5) Reactor Vessel (Plexiglass), (6) Aqueous CuSO_4 Solution, and (7) Iron Screens Substrate

run followed a standardized protocol to ensure reproducibility. Before each run, a stock solution of CuSO_4 was prepared for three initial concentrations: 0.01, 0.02, and 0.03 M. Each run utilized 2.6 L of freshly prepared copper sulfate solution. Also, all glassware, reactor components, and sampling equipment were rigorously cleaned with distilled water followed by acidification with 0.1 M HCl to eliminate trace metal contamination, then rinsed thoroughly with distilled water (Ahmed et al., 2011).

The prepared copper solution was charged into the reactor, and mechanical agitation was initiated at the predetermined speed. All experiments were conducted under ambient temperature conditions (approximately 25 ± 2 °C) with typical run durations of 20 minutes. Temperature control is important as cementation kinetics follow Arrhenius-type temperature dependence with activation energies typically in the range of 15–20 kJ/mol for diffusion-controlled processes (Moats et al., 2000). For each run, liquid samples (5 mL) were withdrawn at 2-minute intervals using a syringe fitted with a filter to exclude any suspended particulates. The high sampling frequency allowed detailed characterization of the temporal concentration profile necessary for accurate mass transfer coefficient determination (Demirkiran et al., 2007). Immediate analysis of each sample minimized potential changes in copper speciation. Following each run, the iron screen was carefully removed and treated with dilute HCl to dissolve the deposited copper layer, facilitating substrate characterization. The cleaned screen was immediately stored under inert atmosphere to prevent iron oxidation. The morphology and adherence of deposited copper significantly influences the cementation rate by altering the effective cathodic surface area (Ku et al., 2002). Copper ion concentration in the aqueous samples was quantified using iodometric titration, a well-established volumetric method offering high precision for Cu^{2+} determination (Wenzel, 2013).—The physical properties of the copper sulfate solutions used in the present study are listed in Table 2 (Abdel-Aziz et al., 2020).

RESULTS AND DISCUSSION

Effect of initial copper concentration

The influence of initial copper concentration on cementation kinetics was investigated across three concentrations (0.01 M, 0.02 M, and 0.03 M) while maintaining constant agitation speed (800 rpm) and screen configuration (5 screens). Figure 2 presents the three-dimensional response surface illustrating the temporal evolution of copper removal efficiency as a function of initial concentration and reaction time. The results demonstrate that copper removal efficiency ranges from approximately 40% to over 85% depending on the operational conditions, with higher removal rates observed at lower initial concentrations.

At the lowest concentration (0.01 M), copper removal reached 82% within 50 minutes, whereas for 0.03 M concentration, removal efficiency was approximately 65% over the same duration. This inverse relationship between initial concentration and removal rate is characteristic of diffusion-controlled cementation processes (Demirkiran et al., 2007; Stefanowicz et al., 1997). The phenomenon can be attributed to several mechanistic factors. First, at higher copper concentrations, the deposition of metallic copper proceeds more

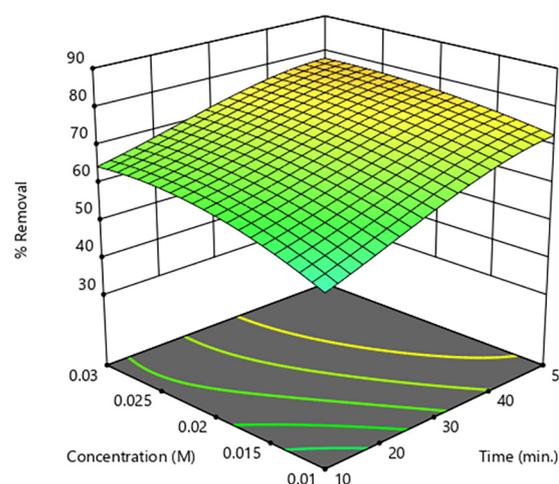


Figure 2. Response surface plot of % removal as a function of time and concentration

Table 2. Physical properties of aqueous CuSO_4 solutions at 25 °C

Concentration of CuSO_4 , M	ρ (g/cm ³)	$\mu \times 10^{-2}$ (g/cm.s)	$D \times 10^{-6}$ (cm ² /s)	Sc
0.01	0.9981	1.0866	6.8	1600
0.02	0.9996	1.0883	6.38	1706
0.03	1.0012	1.1187	6.35	1760

rapidly, potentially leading to faster buildup of copper deposits on the iron surface, which partially blocks active sites and increases diffusion resistance (Karavasteva, 2005). Second, the concentration gradient between the bulk solution and the iron surface, which serves as the driving force for mass transfer, becomes less significant relative to the total copper content at higher concentrations (Ahmed et al., 2011).

This concentration-dependent behavior aligns with previous cementation studies. Recent work by Morsy et al. (Morsy et al., 2025) reported similar trends in zinc-based copper cementation, where removal efficiency decreased from 95% to 78% as copper concentration increased from 100 mg/L to 500 mg/L. Liu et al. (Liu et al., 2023) noted that diffusion-limited processes become increasingly pronounced at elevated metal ion concentrations due to saturation effects near the cementation surface. The present findings also corroborate the mechanistic understanding that cementation kinetics are governed by external mass transfer rather than surface reaction kinetics, particularly when large electrochemical potential differences exist between the cementing metal and target ion (Gros et al., 2011; Makhloufi et al., 2000).

The Schmidt number (Sc) values presented in Table 2 (ranging from 1600 to 1760) confirm the high viscous-to-diffusive ratio characteristic of copper sulfate solutions, indicating that molecular diffusion is inherently slow and that convective mixing becomes critical for enhancing mass transfer (Joshi et al., 2023; Moats et al., 2000). The increasing Sc with concentration further substantiates why higher concentrations exhibit reduced removal efficiencies despite higher absolute amounts of copper being recovered.

Effect of rotation speed

The impact of agitation intensity on copper removal was examined by varying impeller rotation speed from 100 to 800 rpm while maintaining constant initial concentration (0.02 M) and screen configuration (5 screens). Figure 3 displays the response surface depicting the relationship between rotation speed, time, and removal efficiency. The results reveal a strong positive correlation between stirring intensity and cementation performance, with removal efficiency increasing from approximately 42% at 100 rpm to over 82% at 800 rpm after 50 minutes of operation.

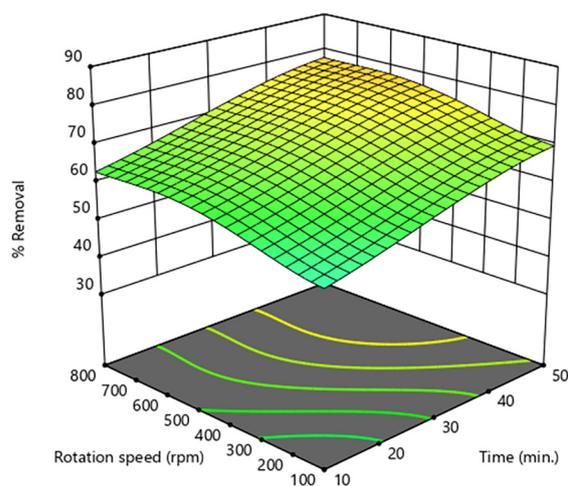


Figure 3. Response surface plot of % removal as a function of time and rotation speed

This enhancement is directly attributable to improved mass transfer conditions generated by increased turbulence at the iron-solution interface (Koseoglu et al., 2022; Paul et al., 2004). Higher rotation speeds reduce the thickness of the diffusion boundary layer surrounding the iron screens, thereby decreasing resistance to copper ion transport from the bulk solution to the reactive surface (Cussler, 2009). Additionally, vigorous agitation generates higher wall shear stresses that continuously remove passivating layers and loosely adherent copper deposits from the screen surface, maintaining exposure of fresh iron for ongoing cementation (Ku et al., 2002; Shahrivar et al., 2020).

The enhancement in mass transfer with increased agitation is well-documented in the literature. In a recent study on copper cementation in rotating systems, it was found that recovery efficiency improved by approximately 40% when agitation was intensified from low to high speeds (Li et al., 2022). Similar observations were reported in wiper-assisted cementation reactors, where mechanical surface renewal enhanced copper removal to near-completion within 10 minutes under optimized conditions (Fathalla et al., 2025). The relationship between turbulence and mass transfer coefficient typically follows power-law correlations of the form $Sh = aRe^b \cdot Sc^c$, where Reynolds number (Re) captures the effect of agitation intensity (Armenante and Nagamine, 1998; Gelves et al., 2014).

However, practical considerations limit the maximum applicable rotation speed. Excessive agitation can lead to vortex formation, air entrainment, and increased power consumption without

proportional gains in mass transfer (Mazumdar and Evans, 2009). Furthermore, very high shear forces may cause mechanical damage to deposited copper and complicate product recovery (Abdel-Aziz, 2011). The present configuration with pitched-blade turbine impellers provides an optimal balance between axial pumping capacity and energy efficiency for solid-liquid contacting operations (Armenante and Nagamine, 1998; Paul et al., 2004).

Effect of number of iron screens

The influence of reactive surface area was evaluated by varying the number of iron screens from 3 to 7 while maintaining constant rotation speed (800 rpm) and initial concentration (0.02 M). Figure 4 illustrates the three-dimensional response surface showing the effect of screen number and time on removal efficiency. Surprisingly, the results reveal a non-monotonic relationship, with an optimal performance observed at intermediate screen configurations (approximately 4–5 screens), achieving removal efficiencies exceeding 75%.

This unexpected behavior suggests that simply increasing the available surface area does not guarantee proportional enhancement in cementation performance. Several competing phenomena explain this observation. While additional screens increase the total reactive surface area, they simultaneously increase the solid volume fraction within the reactor, which can interfere with fluid circulation patterns and reduce mixing effectiveness (Abdel-Aziz et al., 2020; Gros et al., 2008). The presence of multiple screens creates flow obstructions that diminish the hydrodynamic efficiency of the impeller, potentially leading to stagnant zones with reduced mass transfer rates (Joshi et al., 2023).

The optimal screen configuration represents a balance between maximizing reactive surface area and maintaining adequate fluid mixing. Too few screens limit the available iron surface for copper deposition, while excessive screens compromise the hydrodynamic conditions necessary for effective mass transfer (Amin and El-Ash-toukhy, 2011; Gros et al., 2008). This finding is particularly relevant for industrial scale-up, where reactor design must consider both geometric parameters and fluid dynamics.

Recent studies have reported similar phenomena in gas-liquid and solid-liquid systems. Research on screen-based reactors for heavy metal

removal found that cementation rates initially increased with screen number but plateaued or decreased beyond an optimal configuration due to flow channeling and reduced turbulent intensity (Abdel-Aziz et al., 2020; Ibrahim et al., 2021). Advanced computational fluid dynamics simulations of stirred tank reactors have demonstrated that solid volume fractions above 10–15% can significantly impair mixing performance and create dead zones (Gelves et al., 2014; Joshi et al., 2023). The present system employs iron screens positioned along the reactor wall, which theoretically minimizes interference with the central mixing zone generated by the impeller. However, the results suggest that even peripheral placement affects the overall hydrodynamic regime at higher screen densities. This highlights the importance of integrated design approaches that simultaneously optimize chemical kinetics, mass transfer, and fluid dynamics (Mazumdar and Evans, 2009; Paul et al., 2004).

Statistical analysis and model development

To comprehensively analyze the interactive effects of operational parameters and develop a predictive model, response surface methodology (RSM) was employed using a Box-Behnken experimental design. This statistical approach enables systematic investigation of multi-variable processes and identification of optimal operating conditions while minimizing experimental effort (Montgomery, 2017; Myers et al., 2016). The quadratic regression model developed correlates copper removal efficiency with four independent

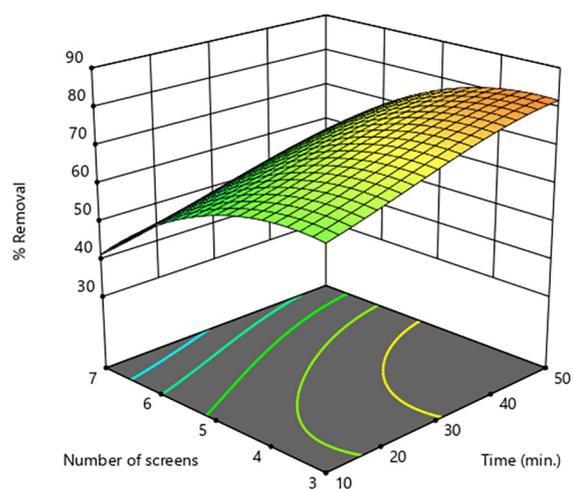


Figure 4. Response surface plot of % removal as a function of time and number of screens

variables: time (A), initial concentration (B), rotation speed (C), and number of screens (D).

Table 3 presents the fit statistics for the developed model, demonstrating excellent predictive capability. The coefficient of determination (R^2) of 0.9846 indicates that 98.46% of the variability in copper removal can be explained by the model, suggesting strong correlation between predicted and experimental values (Hayati et al., 2023). The adjusted R^2 (0.9824) and predicted R^2 (0.9784) values are in close agreement, confirming model robustness without overfitting (Yousefzadeh et al., 2020). The low coefficient of variation (2.51%) indicates high precision and reliability of the experimental procedure (Nizamoğlu et al., 2024). The adequate precision ratio of 92.24, which measures the signal-to-noise ratio, far exceeds the minimum threshold of 4, demonstrating excellent model discrimination (Montgomery, 2017; Myers et al., 2016).

Figure 5 presents the parity plot comparing predicted versus actual copper removal values. The data points align closely along the 45-degree line across the entire range of removal efficiencies (30% to 95%), with minimal scatter, visually confirming the model’s predictive accuracy. This strong correlation validates the appropriateness of the quadratic model structure for capturing the system’s behavior (Hayati et al., 2023; Yousefzadeh et al., 2020).

Table 4 provides the final regression equation in terms of coded factors, revealing the relative importance and nature of each variable’s contribution. The positive coefficients for time (8.37),

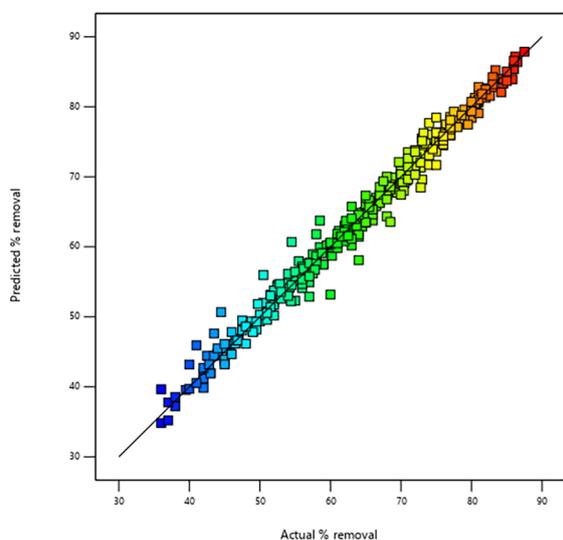


Figure 5. Predicted % removal vs. actual % removal

Table 3. Fit statistics

Std. Dev.	1.63	R^2	0.9846
Mean	64.86	Adjusted R^2	0.9824
C.V. %	2.51	Predicted R^2	0.9784
		Adeq precision	92.2399

initial concentration (3.84), and rotation speed (4.62) indicate their favorable effects on removal efficiency within the studied range (Montgomery, 2017). Notably, the number of screens exhibits a large negative quadratic term (-5.10), mathematically confirming the non-monotonic relationship observed experimentally and explaining the existence of an optimal screen configuration (Myers et al., 2016). The interaction terms in the model provide insights into synergistic and antagonistic effects. The negative interaction coefficient for time-concentration ($AB = -1.03$) suggests that the beneficial effect of extended reaction time diminishes at higher concentrations, consistent with mass transfer limitations (Demirkıran et al., 2007). Similarly, the negative time-rotation speed interaction ($BC = -1.27$) implies that the advantage of high agitation intensity becomes less pronounced during later stages of cementation when copper concentration has decreased (Koseoglu et al., 2022).

Process optimization

Figure 6 displays the optimization results using numerical methods implemented in

Table 4. Final equation in terms of coded factors

% Removal	=
+68.16	
+8.37	A
+3.84	B
+4.62	C
-11.06	D
-1.03	AB
-0.0294	AC
+0.1463	AD
-1.27	BC
-0.1794	BD
-0.4903	CD
-1.48	A ²
+0.3392	B ²
+1.44	C ²
-5.10	D ²

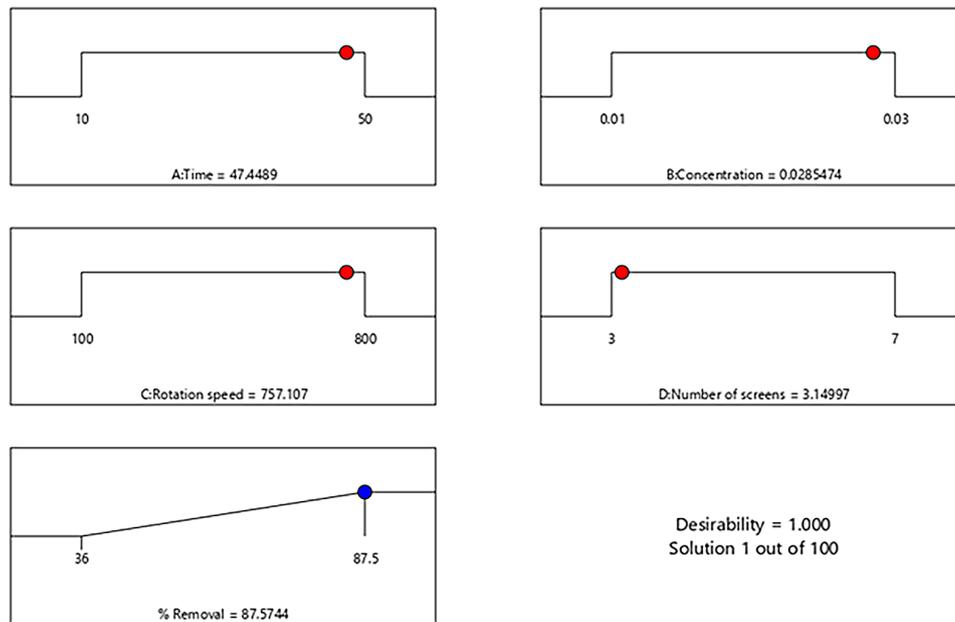


Figure 6. Optimum conditions for achieving maximum % removal of ammonia

Design-Expert software to identify operational conditions maximizing copper removal efficiency while maintaining process desirability. The optimization algorithm simultaneously considered all four factors and their interactions to determine the optimal configuration (Bezerra et al., 2008; Ferreira et al., 2007). The desirability function approach yielded optimal conditions as follows: time = 47.4 minutes, initial concentration = 0.0295 M (near the upper limit), rotation speed = 757 rpm, and number of screens = 3.14 (approximately 3 screens). Under these conditions, the model predicts a maximum copper removal efficiency of 87.57%, with a desirability index of 1.000, indicating perfect satisfaction of the optimization criteria (Costa et al., 2011; Derringer and Suich, 1980).

These optimization results provide valuable practical guidance for process design and operation. The relatively short optimal time (47.4 minutes) represents a favorable characteristic for industrial implementation, offering reasonable throughput without requiring excessively large reactors (Li et al., 2024). The high optimal rotation speed (757 rpm) confirms that vigorous agitation is crucial for maximizing performance, though it remains below the maximum tested value, suggesting the optimal balance between mass transfer enhancement and energy consumption (Abdel-Aziz, 2011; Paul et al., 2004). The optimal screen configuration of approximately 3 screens corroborates the earlier finding that excessive

screens impair performance despite increasing surface area. This result emphasizes that reactor design must prioritize hydrodynamic optimization rather than simply maximizing interfacial area (Armenante and Nagamine, 1998). For industrial applications, this translates to simplified reactor configurations that facilitate easier fabrication, installation, and maintenance (Gros et al., 2008). The optimal initial concentration near the upper limit (0.0295 M, approximately 1880 mg/L Cu^{2+}) is particularly significant from an economic perspective. Higher copper concentrations in industrial wastewater make recovery operations more viable, as the value of recovered copper increases while treatment volume decreases (Gowayed et al., 2025; Li et al., 2024). The present system demonstrates effective performance even at elevated concentrations, indicating suitability for treating concentrated industrial effluents from electroplating, mining, and electronics manufacturing (Ab Hamid et al., 2022; Liu et al., 2023).

CONCLUSIONS

This investigation successfully demonstrated a sustainable and highly effective method for copper recovery from synthetic wastewater through iron screen-assisted cementation within a mechanically stirred batch reactor. The study provides several key findings and contributions that underscore the practical viability of this approach.

The process performance achieved superior results, with copper removal efficiencies consistently reaching 82–88% within a short time-frame of 47–50 minutes under optimized operating conditions, thus establishing its potential for industrial wastewater treatment applications. Detailed parametric studies revealed that cementation efficiency is significantly influenced by key variables, including initial copper concentration, rotational speed, reaction time, and the number of iron screens used. Optimal conditions were precisely identified as a 0.0295 M initial concentration, 757 rpm agitation, a 47.4 minute reaction period, and the deployment of three iron screens.

Furthermore, statistical modeling using response surface methodology (RSM) provided a robust representation of the system's behavior, exhibiting exceptional predictive accuracy ($R^2 = 0.9846$). This reliable model is crucial for aiding both process optimization and scale-up calculations. Analysis of the controlling mechanism confirmed that the overall rate of the process is governed by external mass transfer rather than surface reaction kinetics, implying that hydrodynamic conditions and agitation intensity exert the dominant influence on performance.

From an engineering perspective, the iron screen-stirred tank configuration presents distinct practical advantages: it is characterized by operational simplicity, moderate capital and operational costs, the benefit of directly recovering metallic copper, and a straightforward pathway for scale-up when compared to alternative technologies. Crucially, the process strongly aligns with circular economy principles by effectively transforming a waste stream into a valuable resource, offering both minimal environmental impact and reasonable economic returns.

REFERENCES

1. Ab Hamid, N. H., bin Mohd Tahir, M. I. H., Chowdhury, A., Nordin, A. H., Alshaikh, A. A., Suid, M. A.,...Rushdan, A. I. J. (2022). The current state-of-art of copper removal from wastewater: A review. *Water* 14(19), 3086. <https://doi.org/10.3390/w14193086>
2. Abdel-Aziz, E., El-Naggar, M., Nosier, S., Mubarak, A., Abdel-Aziz, M., Sedahmed, G. J. M. (2020). Recovery of copper from industrial waste solutions by cementation using a rotating fixed bed of stacked steel screens. *Mining, Metallurgy & Exploration* 37(2), 453–458. <https://doi.org/10.1007/s42461-020-00191-z>
3. Abdel-Aziz, M. J. H. (2011). Production of copper powder from wastewater containing CuSO_4 and alcoholic additives in a modified stirred tank reactor by cementation. *Hydrometallurgy* 109(1–2), 161–167. <https://doi.org/10.1016/j.hydromet.2011.06.007>
4. Ahmed, I., El-Nadi, Y., Daoud, J. J. H. (2011). Cementation of copper from spent copper-pickle sulfate solution by zinc ash. *Hydrometallurgy* 110(1–4), 62–66. <https://doi.org/10.1016/j.hydromet.2011.08.007>
5. Al-Saydeh, S. A., El-Naas, M. H., Zaidi, S. J. (2017). Copper removal from industrial wastewater: A comprehensive review. *Journal of Industrial and Engineering Chemistry* 56, 35–44. <https://doi.org/10.1016/j.jiec.2017.07.026>
6. Ali, I., Tan, X., Li, J., Peng, C., Wan, P., Naz, I.,... Ruan, Y. (2023). Innovations in the development of promising adsorbents for the remediation of microplastics and nanoplastics—a critical review. *Water Research* 230, 119526. <https://doi.org/10.1016/j.watres.2022.119526>
7. Amin, N.K, El-Ashtoukhy, E.-S. Z. (2011). Kinetic study of copper cementation onto zinc using a rotating packed bed cylindrical reactor. *Can. J. Chem. Eng.* 89(3), 609–616. <https://doi.org/10.1002/cjce.20443>
8. Armenante, P. M., Nagamine, E. U. (1998). Effect of low off-bottom impeller clearance on the minimum agitation speed for complete suspension of solids in stirred tanks. *Chemical Engineering Science* 53(9), 1757–1775. [https://doi.org/10.1016/S0009-2509\(98\)00001-3](https://doi.org/10.1016/S0009-2509(98)00001-3)
9. Ayala, J., Fernández, B. (2014). Synthesis of commercial products from copper wire-drawing waste. *JOM* 66(6), 1099–1105. <https://doi.org/10.1007/s11837-014-0920-4>
10. Bezerra, M. A., Santelli, R. E., Oliveira, E. P., Villar, L. S., Escaleira, L. A. (2008). Response surface methodology (RSM) as a tool for optimization in analytical chemistry. *Talanta* 76(5), 965–977. <https://doi.org/10.1016/j.talanta.2008.05.019>
11. Costa, N. R., Lourenço, J., Pereira, Z. L. (2011). Desirability function approach: A review and performance evaluation in adverse conditions. *Chemometrics and Intelligent Laboratory Systems* 107(2), 234–244. <https://doi.org/10.1016/j.chemolab.2011.04.004>
12. Cussler, E. L. (2009). *Diffusion: mass transfer in fluid systems*. Cambridge university press. <https://doi.org/10.1017/CBO9780511805134>
13. Demirkıran, N., Ekmekyapar, A., Künkül, A., Bay-sar, A. (2007). A kinetic study of copper cementation with zinc in aqueous solutions. *International*

- Journal of Mineral Processing* 82(2), 80–85. <https://doi.org/10.1016/j.minpro.2006.10.005>
14. Derringer, G., Suich, R. (1980). Simultaneous optimization of several response variables. *Journal of Quality Technology*, 12(4), 214–219. <https://doi.org/10.1080/00224065.1980.11980968>
 15. Fathalla, A., El-Ashtoukhy, E.-S., Abdel-Aziz, M., Sedahmed, G., El-Naggar, M. A. (2025). Surface renewal driven copper recovery by cementation in a stirred reactor with a rotating wiper mechanism. *Scientific Reports* 15(1), 29257. <https://doi.org/10.1038/s41598-025-10845-x>
 16. Ferreira, S. C., Bruns, R., Ferreira, H. S., Matos, G. D., David, J., Brandão, G.,...Souza, A.S. (2007). Box-Behnken design: An alternative for the optimization of analytical methods. *Analytica Chimica Acta* 597(2), 179–186. <https://doi.org/10.1016/j.aca.2007.07.011>
 17. Gelves, R., Dietrich, A., Takors, R. (2014). Modeling of gas–liquid mass transfer in a stirred tank bioreactor agitated by a Rushton turbine or a new pitched blade impeller. *Bioprocess Biosyst Eng.* 37(3), 365–375. <https://doi.org/10.1007/s00449-013-1001-8>
 18. Gowayed, S. M., Abdel-Salam, A. H., Nassef, E., Morsy, A. (2025). Innovative hybrid membrane: Pioneering metal oxide framework for improved elimination of heavy metals from industrial wastewater. *Polym Eng Sci.* 65(4), 2093–2105. <https://doi.org/10.1002/pen.27139>
 19. Gros, F., Baup, S., Aurousseau, M. (2008). Intensified recovery of copper in solution: Cementation onto iron in fixed or fluidized bed under electromagnetic field. *Chemical Engineering and Processing: Process Intensification* 47(3), 295–302. <https://doi.org/10.1016/j.cep.2007.01.002>
 20. Gros, F., Baup, S., Aurousseau, M. (2011). Copper cementation on zinc and iron mixtures: Part 1: Results on rotating disc electrode. *Hydrometallurgy* 106(1–2), 127–133. <https://doi.org/10.1016/j.hydromet.2010.12.011>
 21. Hayati, M., Ganji, S. M. S. A., Shahcheraghi, S. H., Khabir, R. R. (2023). Optimization of copper recovery from electronic waste using response surface methodology and Monte Carlo simulation under uncertainty. *J Mater Cycles Waste Manag* 25(1), 211–220. <https://doi.org/10.1007/s10163-022-01526-2>
 22. Ibrahim, B., Abdel-Aziz, M., El-Ashtoukhy, E. Z., Zewail, T., Zatout, A., Sedahmed, G. (2021). Cementation of copper on zinc in agitated vessels equipped with perforated baffles as turbulence promoters. *Mining, Metallurgy & Exploration* 38(2), 1203–1213. <https://doi.org/10.1007/s42461-020-00375-7>
 23. Joshi, S. S., Dalvi, V. H., Vitankar, V. S., Joshi, A. J., Joshi, J. B. (2023). Novel correlation for the solid–liquid mass transfer coefficient in stirred tanks developed by interpreting machine learning models trained on literature data. *Thermodynamics, Transport, and Fluid Mechanics* 62(46), 19920–19935. <https://doi.org/10.1021/acs.iecr.3c02442>
 24. Justel, F. J., Taboada, M. E., Flores, E. K., Galleguillos, H. R., Graber, T. A. (2020). Thermodynamic model for the design of a process of production of copper sulfate pentahydrate from copper ores. *ACS Omega* 5(45), 29073–29080. <https://doi.org/10.1021/acsomega.0c03615>
 25. Kaepula, V. L., Luis, P. (2024). Removal of heavy metals from wastewater using reverse osmosis. *Frontiers in Chemical Engineering* 6, 1334816. <https://doi.org/10.3389/fceng.2024.1334816>
 26. Karavasteva, M. (2005). Kinetics and deposit morphology of copper cementation onto zinc, iron and aluminium. *Hydrometallurgy* 76(1–2), 149–152. <https://doi.org/10.1016/j.hydromet.2004.10.003>
 27. Karnwal, A., Malik, T. (2024). Nano-revolution in heavy metal removal: engineered nanomaterials for cleaner water. *Frontiers in Environmental Science* 12, 1393694. <https://doi.org/10.3389/fenvs.2024.1393694>
 28. Khuri, A. I., Mukhopadhyay, S. (2010). Response surface methodology. *WIREs Comp Stat.* 2(2), 128–149. <https://doi.org/10.1002/wics.73>
 29. Koseoglu, H., Delikanli, N. E., Gonulsuz, E., Aydin, M. T., Sardohan Koseoglu, T., Yigit, N. O.,...Research, P. (2022). Copper recovery by cementation process from polymeric membrane concentrate flows and sensor integration. *Environ Sci Pollut Res* 29(33), 50256–50270. <https://doi.org/10.1007/s11356-022-19338-0>
 30. Ku, Y., Wu, M.-H., Shen, Y.-S. (2002). A study on the cadmium removal from aqueous solutions by zinc cementation. *Separation Science and Technology* 37(3), 571–590. <https://doi.org/10.1081/SS-120001448>
 31. Li, Q., Wang, Y., Chang, Z., El Kolaly, W., Fan, F., Li, M. (2024). Progress in the treatment of copper (II)-containing wastewater and wastewater treatment systems based on combined technologies: A review. *Journal of Water Process Engineering* 58, 104746. <https://doi.org/10.1016/j.jwpe.2023.104746>
 32. Li, S., Wang, X., Guo, Y., Hu, J., Lin, S., Tu, Y.,...Huang, L. (2022). Recent advances on cellulose-based nanofiltration membranes and their applications in drinking water purification: A review. *Journal of Cleaner Production* 333, 130171. <https://doi.org/10.1016/j.jclepro.2021.130171>
 33. Liu, Y., Wang, H., Cui, Y., Chen, N. (2023). Removal of copper ions from wastewater: a review. *J. Environ. Res. Public Health* 20(5), 3885. <https://doi.org/10.3390/ijerph20053885>
 34. Makhouloufi, L., Saidani, B., Hammache, H. J. W. R. (2000). Removal of lead ions from acidic

- aqueous solutions by cementation on iron. *Water Research* 34(9), 2517–2524. [https://doi.org/10.1016/S0043-1354\(99\)00405-4](https://doi.org/10.1016/S0043-1354(99)00405-4)
35. Mazumdar, D., Evans, J. W. (2009). *Modeling of steelmaking processes*. CRC Press. <https://doi.org/10.1201/b15828>
36. Moats, M. S., Hiskey, J. B., Collins, D. W. (2000). The effect of copper, acid, and temperature on the diffusion coefficient of cupric ions in simulated electrorefining electrolytes. *Hydrometallurgy* 56(3), 255-268. [https://doi.org/10.1016/S0304-386X\(00\)00070-0](https://doi.org/10.1016/S0304-386X(00)00070-0)
37. Montgomery, D. C. (2017). *Design and analysis of experiments*. John Wiley & Sons. <https://doi.org/10.1007/978-3-319-52250-0>
38. Morsy, A., Rahman, H. H. A., Kamel, H. M., Ewais, H. A., Ahmed, A. E. M. M., Morsy, A.,... Blall, E. (2025). Sustainable recovery of copper from wastewater via zinc cementation enhanced by natural chalcone-based accelerators. *Scientific Reports* 15(1), 31304. <https://doi.org/10.1038/s41598-025-16475-7>
39. Myers, R. H., Montgomery, D. C., Anderson-Cook, C. M. (2016). *Response surface methodology: process and product optimization using designed experiments*. John Wiley & Sons. <https://doi.org/10.1080/00224065.2017.11917988>
40. Nizamoğlu, H., Turan, M. D., Sarı, Z. A., Babayeva, P. (2024). Sustainable green industry work: recovery of copper slag with mill scale leaching reactant optimized by response surface methodology (RSM). *Journal of Sustainable Metallurgy* 10(4), 2501–2520. <https://doi.org/10.1007/s40831-024-00944-w>
41. Paul, E. L., Atiemo-Obeng, V. A., Kresta, S. M. (2004). *Handbook of industrial mixing*. Wiley Online Library. <https://doi.org/10.1002/cite.200490408>
42. Shahrivar, E., Karamoozian, M., Gharabaghi, M. (2020). Modeling and optimization of oxide copper cementation kinetics. *SN Applied Sciences* 2(3), 469. <https://doi.org/10.1007/s42452-020-2247-9>
43. Stefanowicz, T., Osińska, M., Napieralska-Zagolda, S. (1997). Copper recovery by the cementation method. *Hydrometallurgy* 47(1), 69-90. [https://doi.org/10.1016/S0304-386X\(97\)00036-4](https://doi.org/10.1016/S0304-386X(97)00036-4)
44. Wang, Z., Luo, P., Zha, X., Xu, C., Kang, S., Zhou, M.,... Wang, Y. (2022). Overview assessment of risk evaluation and treatment technologies for heavy metal pollution of water and soil. *Journal of Cleaner Production* 379, 134043. <https://doi.org/10.1016/j.jclepro.2022.134043>
45. Wenzel, T. J. (2013). Douglas A. Skoog, Donald M. West, F. James Holler, and Stanley R. Crouch: Fundamentals of analytical chemistry, international ed. In: Springer. <https://doi.org/10.1007/s00216-013-7242-1>
46. Wichers, E., Ashley, S., Butler, A., Clarke, B., Collins, W., Eisenhauer, F.,... Wolf, J. (1953). Recommended specifications for reagent chemicals. *Analytical Chemistry* 25(2), 365-380.
47. Yan, C., Qu, Z., Wang, J., Cao, L., Han, Q. (2022). Microalgal bioremediation of heavy metal pollution in water: Recent advances, challenges, and prospects. *Chemosphere* 286, 131870. <https://doi.org/10.1016/j.chemosphere.2021.131870>
48. Yousefzadeh, S., Yaghmaeian, K., Mahvi, A. H., Nasserli, S., Alavi, N., Nabizadeh, R. (2020). Comparative analysis of hydrometallurgical methods for the recovery of Cu from circuit boards: optimization using response surface and selection of the best technique by two-step fuzzy AHP-TOPSIS method. *Journal of Cleaner Production* 249, 119401. <https://doi.org/10.1016/j.jclepro.2019.119401>