Journal of Biomed Research

Praful NK, et al., J Biomed Res.
2025;6(1):88-92.

Commentary

Commentary on the use of the Taguchi method for electrocoagulation optimization in dairy effluent treatment

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Received date: May 26, 2025
Accepted date: July 21, 2025

Abstract

Dairy industry wastewater, characterized by its high load of organic and inorganic pollutants, continues to pose significant challenges to conventional treatment technologies. Electrocoagulation (EC) has emerged as an effective alternative, but its success depends on the careful optimization of multiple interrelated parameters. This commentary builds upon the study *"Comparative Evaluation Between Taguchi Method and Response Surface Method for Optimization of Electrocoagulation Process in the Context of Treatment of Dairy Industry Wastewater"* by Praful *et al.*, which benchmarked the Taguchi method against Response Surface Methodology (RSM) for EC process optimization. While RSM offers flexibility in modeling complex interactions, the Taguchi method stands out for its experimental simplicity, reduced resource demand, and practical applicability in real-world settings. This commentary critically evaluates the strengths and limitations of the Taguchi method and positions it not as an endpoint but as a foundational method that can be extended through hybridization. By advocating for the integration of Taguchi with modern computational and decision-support tools, this article proposes a roadmap for developing more adaptive, intelligent, and multi-objective optimization strategies in industrial wastewater treatment.

Keywords: Dairy wastewater, Electrocoagulation, Taguchi method, Statistical optimization, Hybrid modeling

Introduction

The treatment of dairy industry wastewater has become an increasingly critical environmental concern due to its high organic and inorganic pollutant load, including elevated levels of Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and nitrates [1–3]. As one of the largest contributors to the global food processing sector, the dairy industry generates vast volumes of complex effluents rich in fats, proteins, lactose, suspended solids, and dissolved inorganic compounds [4]. When discharged untreated, these effluents can significantly degrade water quality, leading to eutrophication, oxygen depletion, and serious risks to public health and aquatic ecosystems [5–7]. Conventional treatment methods—such as biological processing and chemical coagulation—often fall short in addressing the high-strength and variable nature of dairy wastewater [8].

In this regard, electrocoagulation (EC) has become an exciting substitute for water treatment [9–11]. Usually, aluminum or iron is used as electrodes in the EC process [12–14]. EC is an electrochemical treatment method whereby electric current causes metal electrodes to dissolve, therefore producing coagulant species *in situ* [15]. Coagulation, adsorption and flotation together assist these species in removing contaminants from wastewater. Among the additional benefits the system delivers are operational simplicity, minimum consumption of chemicals, and substantial contamination removal efficiency [16]. However, reaching its full potential demands fine-tuning of operating parameters such as applied voltage, electrolysis time, current density, and inter-electrode (IED) spacing [15].

This commentary builds on the findings of the study titled "Comparative Evaluation Between Taguchi Method and Response Surface Method for Optimization of Electrocoagulation Process in the Context of Treatment of Dairy Industry Wastewater [17]". The original work compared the effectiveness of two statistical approaches—Taguchi Method [18] and Response Surface Methodology (RSM) [19] for optimizing the electrocoagulation (EC) process [17,20,21]. Although both techniques produced valuable results, this commentary focuses on the Taguchi Method, emphasizing its practical advantages, methodological simplicity, and growing application in environmental engineering. In addition, this commentary proposes integrating the Taguchi Method with Grey Relational Analysis (GRA) to develop a hybrid Taguchi-GRA framework [22,23]. This combination offers a more robust optimization technique, particularly suited for multi-response decision-making in complex industrial effluent treatment, such as dairy wastewater. By proposing this hybrid approach, the commentary extends the topic beyond the original study, addressing both the strengths and limits of the Taguchi Method and stressing its evolving importance in the development of scalable and economical wastewater treatment solutions.

Strengths and Practical Relevance of the Taguchi Method

The Taguchi method, built on the robust design principles developed by [24], is widely recognized for its effectiveness in the optimization of complex processes with a minimal number of experimental trials. In the study conducted done by Praful *et al.* (2024), the Taguchi approach was applied using an L9 orthogonal array—a standardized experimental design that enabled a systematic investigation of three critical process variables: voltage (5, 15, and 25 V), electrolysis time (30, 60, and 90 minutes), and inter-electrode distance (1.0, 1.5, and 2.0 cm), each evaluated at three distinct levels [17]. This setup was carefully chosen to assess the performance of the electrocoagulation (EC) process in treating dairy industry wastewater, with a specific focus on improving the removal efficiencies of BOD, COD, and nitrate.

A total of nine experimental runs were conducted according to the L9 orthogonal array [18,23,25]. This approach significantly reduced the experimental workload when compared to a full factorial design, which would have required 27 runs [26,27]. The performance outputs from each run were assessed using the signal-to-noise (S/N) ratio, applying the "larger-the-better" criterion [22]. This criterion is appropriate for maximizing pollutant removal efficiencies. The S/N ratio effectively captured the variability of each response and provided a quantitative measure of the robustness of the process parameters. Based on the analysis of S/N ratios and the corresponding response tables. The study identified the optimal conditions for pollutant removal as a Voltage of 25 V, 90 minutes of electrolysis time, and an IED of 1.0 cm. The results indicated that the Taguchi method not only matched the performance of RSM. But, in some cases, even surpassed its efficiency, despite RSM typically being more computationally intensive. Under these optimized conditions, the removal efficiencies achieved were 90.14% for BOD, 89.12% for COD, and 82.42% for nitrates [17].

One of the method's core advantages lies in its experimental efficiency and the number of trials required for the study [24]. While RSM required 15 runs using a Box-Behnken design (BBD) to explore interactions and quadratic effects, while the Taguchi method required only 9 trials, significantly reducing time, resource consumption, and experimental complexity [28,29]. This makes it particularly attractive in real-world applications where rapid prototyping and resource efficiency are critical. Furthermore, by focusing on signal-to-noise (S/N) ratios, the method provides a practical metric for evaluating performance robustness under variable operating conditions—a significant advantage when treating wastewater from diverse streams with fluctuating compositions, such as dairy wastewater [30].

Another noteworthy strength of the Taguchi method is its modular and adaptable structure, which makes it ideal for integrating with other decision-making tools. It can serve as a foundational framework in multi-objective optimization contexts, where factors such as treatment efficiency, operational cost, and energy usage must all be balanced. However, while powerful in terms of primary effect analysis, the Taguchi method traditionally falls short in its capacity to fully model the interaction effects and manage multiple conflicting responses simultaneously—a gap that can be addressed by incorporating GRA [27].

Limitations of the Taguchi Method and the Case for Hybridization

Despite its several advantages in simplicity and efficiency, the Taguchi method is not without some limitations. One of the most cited drawbacks is its inability to capture complex variable interactions, especially higher-order relationships or non-linear relationships between parameters, in processes like EC, where major operating conditions such as voltage, duration, and IED may interact in non-obvious ways to influence contaminant removal, which may lead to suboptimal predictions [31]. Unlike RSM, which explicitly models quadratic and interaction effects, the standard Taguchi methods framework mainly focuses on the main effects of individual factors, which can sometimes lead to an oversimplified representation of the model. In environmental engineering, chemical engineering with respect to water or wastewater treatment, optimizing a single performance response (like BOD, COD or nutrient removal) is rarely sufficient, as multiple factors typically need to be balanced simultaneously [32]. Instead, decision makers or policymakers must simultaneously consider multiple parameters, often conflicting objectives such as COD or BOD reduction, nitrate removal, energy effectiveness, and cost efficiency in the model. The classical Taguchi method does not natively support such multi-objective trade-offs, limiting its utility when a holistic evaluation of system performance is needed [33].

To overcome these constraints, researchers and scientists have increasingly switched to hybrid approaches, most notably the merging of the Taguchi method with GRA. GRA is a powerful tool for analyzing systems with incomplete or uncertain information, particularly in multi-criteria decision-making [36]. Integrating Taguchi-based experimental design with the Taguchi-GRA hybrid model allows the transformation of multiple responses into a single composite grey relational grade (GRG). This facilitates the simultaneous optimization of all the responses in the experimental design models. This hybrid framework not only preserves the Taguchi method's efficiency but also enhances its ability to manage multi-response scenarios with greater accuracy and decision-making strength. The Taguchi-GRA approach offers a compelling balance between statistical rigor and practical feasibility in applications such as dairy wastewater treatment, where multiple pollutants must be controlled simultaneously [33–35].

Future Directions for Taguchi-based Hybrid Optimization in Water Treatment

As water and wastewater treatment systems become increasingly complex—due to heterogeneous influent compositions, tightening environmental regulations, and ambitious sustainability goals—traditional single-response optimization methods such as the Taguchi technique are becoming progressively inadequate [36]. Despite its wide recognition for experimental efficiency, ease of implementation, and capability to identify optimal process parameters with relatively few trials, the Taguchi method's univariate focus limits its applicability in modern treatment scenarios. These contemporary systems demand the simultaneous optimization of multiple, often interdependent, performance indicators, such as BOD, COD, turbidity, nutrient removal efficiency, sludge production, and energy consumption [37]. To overcome these limitations, recent research has increasingly shifted toward hybrid optimization models that extend the classical Taguchi method by integrating it with analytical, computational, and decision-support tools. These Taguchi-based hybrid approaches enable multi-response, multi-objective, and uncertainty-informed optimization, offering a more comprehensive framework for improving water treatment performance [38]. The following section delineates several prominent hybrid Taguchi models that are being actively explored in the context of water treatment optimization.

Key Taguchi-based hybrid optimization techniques in water treatment

Taguchi–Grey Relational Analysis (GRA): GRA is particularly effective for optimizing multiple response variables that vary in scale or measurement units. By standardizing output parameters and consolidating them into a unified GRG, this approach enables simultaneous assessment of treatment performance [22]. In processes such as electrocoagulation, adsorption, and advanced oxidation, the Taguchi–GRA framework has been shown to improve the collective removal efficiency of pollutants, including BOD, COD, and nitrates [17,39].

Taguchi–Principal Component Analysis (PCA): PCA mitigates the challenge of multicollinearity among response variables by converting correlated metrics into a smaller set of orthogonal principal components [40]. While traditional Taguchi–PCA models often rely on signal-to-noise ratios and may inadequately represent underlying correlations, recent methodologies incorporating weighted PCA corrections offer enhanced accuracy. These refinements have demonstrated improved performance in optimizing complex, chemically intensive treatment systems [37].

Taguchi–Analytical Hierarchy Process (AHP): AHP offers a systematic approach for evaluating and prioritizing multiple criteria through pairwise comparisons [41]. When integrated with the Taguchi design of experiments, AHP facilitates informed decision-making regarding water treatment configurations. It supports the comparative assessment of alternatives based on multiple attributes, such as treatment efficiency, economic feasibility, maintenance demands, and regulatory compliance, making it particularly beneficial for strategic process selection [40].

Taguchi–Fuzzy logic systems*:* Fuzzy logic is well-suited for managing uncertainty and imprecision in operational contexts where influential characteristics are highly variable and exact performance targets may be vague. Integrating fuzzy logic with the Taguchi method allows for the construction of a multi-criteria performance index using qualitative linguistic variables (e.g., "high," "medium," "low"). This hybrid approach has been effectively implemented in optimizing tasks such as pre-treatment operations, coagulant dosing strategies, and human-supervised process adjustments [41].

Taguchi–Artificial Neural Networks (ANN): ANNs are increasingly utilized to model complex nonlinear dynamics and predict system behavior in real-time water treatment applications. However, optimizing ANN parameters typically relies on heuristic methods [42]. The incorporation of Taguchi-based experimental design can enhance this process by systematically optimizing key parameters—including learning rates, network depth, and momentum values—thereby improving the network's training performance and predictive reliability, especially in sensor-integrated and automated treatment systems[42,43].

The integration of the Taguchi method with computational and decision-making techniques signifies a critical advancement in the optimization of wastewater treatment processes. These hybrid approaches effectively address the limitations of traditional single-response optimization by accommodating the multi-variable, dynamic, and uncertain nature of real-world wastewater operations. By enabling the simultaneous optimization of key treatment performance metrics, such as BOD, COD, nutrient removal, sludge production, and energy consumption, these models offer a more holistic and evidence-based approach to process improvement.

Their relevance is particularly pronounced in the context of digital advancements in wastewater management, where real-time data acquisition, automated control systems, and intelligent monitoring are becoming integral components of treatment infrastructure. To fully exploit the potential of Taguchi-based hybrid models in wastewater treatment, future research and operational practice should emphasize:

- Experimental validation across pilot- and full-scale wastewater treatment facilities to ensure practical applicability;
- Integration with real-time process control systems, including IoT-based sensors, programmable logic controllers (PLCs), and SCADA platforms;
- Comprehensive techno-economic and environmental assessments to evaluate lifecycle performance, cost-effectiveness, and sustainability outcomes.

These efforts will be instrumental in shaping next-generation wastewater treatment systems that are not only efficient and adaptive but also aligned with evolving environmental regulations and resource sustainability goals.

Conclusion

The foundational study by Praful *et al.* demonstrated the effectiveness of the Taguchi Method in optimizing electrocoagulation parameters for the treatment of dairy industry wastewater. Their research showcased how the Taguchi approach, through its use of orthogonal arrays and signal-to-noise ratios, can achieve high removal efficiencies for BOD, COD, and nitrates with a limited number of experimental trials—making it highly attractive for industrial applications that demand simplicity, speed, and cost-effectiveness.

However, this commentary contends that while the Taguchi Method is valuable in its current form, it must evolve to meet the growing demands of modern wastewater treatment systems. Specifically, the method's limitations in handling interaction effects and multi-objective optimization highlight the need for a more integrated approach.

To that end, this paper advocates for the development of Taguchi-based hybrid optimization frameworks. By combining the Taguchi design of experiments with computational tools such as artificial neural networks, fuzzy logic systems, principal component analysis, and machine learning algorithms, researchers can create robust, adaptive models capable of addressing the complex, dynamic, and multi-response nature of real-world effluent streams.

In conclusion, the work of Praful *et al*. provides a strong foundation upon which future enhancements can be built. By extending the Taguchi Method into hybrid domains, environmental engineers and practitioners can unlock scalable, intelligent, and sustainable solutions for industrial wastewater treatment in the era of smart process control and data-driven decision-making.

Acknowledgement

The authors extend their sincere gratitude to the Department of Civil Engineering at Symbiosis Institute of Technology, the Symbiosis Institute of Geoinformatics, Symbiosis International (Deemed University), Pune, and the Institute of Environment Education and Research, Bharati Vidyapeeth (Deemed to be University), Pune, for their invaluable support in facilitating this research work.

Authors' Contribution

Praful N K: Methodology, Data Curation, Software, Formal Analysis, Writing–Original Draft; **Binaya Kumar Pattnaik:** Supervision, Conceptualization, Validation, Writing – Review & Editing; **Sandipan Das:** Supervision, Conceptualization, Validation, Writing – Review & Editing.

Data Availability

Data will be provided on request.

Funding

Not applicable.

Declarations

Ethical approval

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of authors" as found in the Instructions for Authors.

Consent to publish

All authors have agreed to submit the manuscript in its current form for consideration for publication in the journal.

Competing interests

The authors declare no conflict of interest.

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