Journal of Sustainable Economy

Journal homepage: https://scholarsin.com/journals/sustainable-economy

Factors Affecting the Efficiency of Wastewater Treatment Processes in Industrial Cities in Libya: A Quantitative Study in Brega and Ras Lanuf

Ziyad Abdulmajid Almasori[1] and Omar Emad Hassouna[1]

[1]*School of Engineering, Alfa University College, Selangor, Malaysia*

ABSTRACT

Industrial wastewater management presents a critical environmental challenge in Libya's hydrocarbon-dependent economy, particularly within the major coastal industrial complexes of Brega and Ras Lanuf. This quantitative study investigates the factors affecting wastewater treatment efficiency in these industrial cities, focusing on Influent Organic Loading Rate (OLR), Hydraulic Retention Time (HRT), and Physico-Chemical Conditions (pH and temperature) as key operational parameters. Grounded in System Theory and Monod Kinetics, the research employed a descriptive-correlational, cross-sectional survey design with 120 technical professionals from National Oil Corporation facilities. Multiple linear regression analysis revealed that the three independent variables collectively explain 55.1% of the variance in treatment efficiency ($R^2 = 0.551$, $F = 46.682$, $p < 0.001$). Physico-Chemical Conditions emerged as the strongest positive predictor ($\beta = 0.412$, $p < 0.001$), followed by OLR, which exerted a significant negative effect ($\beta = -0.351$, $p < 0.001$), and HRT, demonstrating a significant positive contribution ($\beta = 0.298$, $p < 0.001$). These findings provide empirical evidence that environmental boundary controls and organic load equalization are primary prerequisites for process optimization. The study offers actionable guidance for facility managers and policymakers to enhance operational performance, ensure environmental compliance, protect Mediterranean coastal ecosystems, and advance sustainable water reuse in North Africa's water-scarce region.

Keywords: Wastewater treatment efficiency, organic loading rate, hydraulic retention time, physico-chemical conditions, industrial wastewater, Libya, Brega, Ras Lanuf

[1] Corresponding author.

Email address: omar.i@alfa.edu.my (Omar Emad Hassouna)

Received 1 Jun 2026; Received in revised form 13 July 2026; Accepted 27 July 2026

Available online 31 July 2026

ISSN: 0231-2618/

1. Introduction

The global industrial sector faces mounting pressure to consume natural resources efficiently while maintaining stringent environmental and economic sustainability standards. Within hydrocarbon-dependent economies such as Libya, industrial wastewater management represents a critical environmental engineering challenge, directly influencing water security, public health, and ecological preservation. The safeguarding of limited freshwater resources in North Africa is no longer merely a regulatory compliance issue, but an essential operational strategy for survival in an increasingly arid region facing acute water scarcity. Wastewater Treatment Plants (WWTPs) serve as indispensable environmental barriers within industrial ecosystems, transforming toxic, high-strength industrial byproducts generated during petroleum refining, gas processing, and petrochemical manufacturing into reusable or ecologically safe effluents. In the major coastal industrial complexes of Brega and Ras Lanuf—which house Libya's primary crude oil export terminals, petroleum refineries, and ethylene derivatives plants—optimizing wastewater treatment efficiency is a vital operational mandate required to protect the sensitive Mediterranean marine coastline and alleviate severe national water stress through industrial water reclamation (Abmdas et al., 2026; Aghow, 2025).

The operational performance of industrial wastewater treatment systems is governed not by a single process variable, but rather by a complex, non-linear interaction of hydraulic, chemical, and biological operational parameters. Primary among these operating parameters is the Influent Organic Loading Rate (OLR), which dictates the total substrate mass entering the biological treatment reactors per unit volume per day. While moderate organic loads stimulate microbial growth and metabolic degradation, severe organic shock loading—a frequent occurrence during refinery unit turnarounds or chemical washings—overwhelms biological sludge, induces toxic shock, and triggers process failure (Abmdas et al., 2026; Ghannadzadeh et al., 2023). However, organic substrate conversion cannot occur without sufficient Hydraulic Retention Time (HRT), which dictates the physical contact duration between dissolved pollutants and treatment biomass; inadequate retention times prevent complete microbial breakdown and result in active biomass washout (Drouiche et al., 2020). Compounding these hydraulic and organic loading stressors are local Physico-Chemical Conditions—specifically ambient and fluid temperature and pH levels. Extremes in wastewater pH or thermal spikes exceeding 40°C severely suppress enzymatic activity, inhibit nitrifying bacteria, and lower dissolved oxygen saturation in aeration basins, severely degrading treatment performance regardless of retention time or design capacity (Tertouche et al., 2021; Mateo-Sagasta et al., 2018).

Despite the recognized importance of these parameters, a critical empirical knowledge gap persists regarding their combined statistical impact on treatment plant efficiency within the industrial context of Libya. Existing Libyan studies have largely focused on single-point chemical sampling (Abusaloua, 2015), high-level national policy reviews (CEDARE, 2005; Fanack Water, 2022), or bench-scale laboratory experiments (Tertouche et al., 2021), leaving an absence of quantitative field research evaluating operational plant performance. Consequently, facility managers and process engineers at Brega and Ras Lanuf lack evidence-based models to guide operational decision-making, frequently resulting in reactive maintenance, sub-optimal flow equalization, and frequent non-compliant industrial discharges containing elevated Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and Total Petroleum Hydrocarbons (TPH) (Aghow, 2025; Hu et al., 2019). To address this critical gap, this research formulates three primary research questions: (1) What is the relationship between Influent Organic Loading Rate and treatment efficiency in industrial wastewater plants in Brega and Ras Lanuf? (2) What is the relationship between Hydraulic Retention Time and treatment efficiency? (3) What is the relationship between Physico-

Chemical Conditions (pH and temperature) and treatment efficiency? Correspondingly, the main research aim is to quantitatively evaluate the individual and collective impacts of Influent Organic Loading Rate (IV1), Hydraulic Retention Time (IV2), and Physico-Chemical Conditions (IV3) on Wastewater Treatment Efficiency (DV) across industrial facilities in Brega and Ras Lanuf. The specific research objectives are: (RO1) to evaluate the impact of Influent Organic Loading Rate on treatment efficiency; (RO2) to analyze the impact of Hydraulic Retention Time on treatment efficiency; and (RO3) to examine the impact of Physico-Chemical Conditions on treatment efficiency. Based on environmental engineering principles, three central hypotheses are posited: H1 states that there is a significant negative relationship between Influent Organic Loading Rate and treatment efficiency; H2 states that there is a significant positive relationship between Hydraulic Retention Time and treatment efficiency; and H3 states that there is a significant positive relationship between favorable Physico-Chemical Conditions and treatment efficiency.

The practical and theoretical significance of this research is substantial. Practically, the study equips facility managers at the Brega and Ras Lanuf oil complexes with an empirical diagnostic tool to optimize operational expenditure (OPEX), refine flow regulation schedules, and adjust pH dosing and aeration controls to maximize pollutant removal and prevent environmental contamination along the Libyan coast. Theoretically, this study advances environmental engineering literature by integrating System Theory and Monod Kinetics into a quantitative empirical framework validated within an under-researched, water-stressed industrial environment in North Africa. For the purpose of this study, Influent Organic Loading Rate (IV1) is operationally defined as the organic substrate mass (BOD and COD in mg/L) introduced into the treatment system per unit volume per day (Abmdas et al., 2026). Hydraulic Retention Time (IV2) is operationally defined as the mean contact duration (in hours) that wastewater resides within biological treatment reactors (Drouiche et al., 2020). Physico-Chemical Conditions (IV3) refer to the measured operational temperature (°C) and acidity/alkalinity (pH) environment within the treatment tanks (Tertouche et al., 2021). Wastewater Treatment Efficiency (DV) is operationally defined as the percentage removal efficiency of key water quality indicators, specifically BOD, COD, Total Suspended Solids (TSS), and Total Petroleum Hydrocarbons (TPH) (Mateo-Sagasta et al., 2018).

2. Literature Review

Industrial wastewater treatment efficiency relies on fundamental biological, physical, and chemical unit operations designed to reduce environmental pollutant concentrations to safe discharge or reuse standards. Treatment performance is benchmarked quantitatively through percentage removal metrics for Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), and Total Petroleum Hydrocarbons (TPH) (Mateo-Sagasta et al., 2018; Nikiema et al., 2024). In heavy industrial and refining complexes, raw effluent contains complex emulsions of hydrocarbons, heavy metals, phenols, and dissolved gases that resist standard municipal secondary biological treatment alone (Hu et al., 2019; Frascari et al., 2018). Global research demonstrates that biological treatment processes (e.g., activated sludge, trickling filters, and membrane bioreactors) can achieve 70–95% organic contaminant removal under stable operating conditions, but efficiency deteriorates rapidly when systems experience hydraulic surges or organic overloading (Korotkova et al., 2019; Nikiema et al., 2024).

Influent Organic Loading Rate (OLR) is a primary operational determinant of biological wastewater treatment efficiency. Governed by Monod microbial growth kinetics, biological degradation rates increase proportionally with substrate concentration up to a saturation threshold, beyond which substrate inhibition occurs (Ghannadzadeh et al., 2023). In petroleum refining and petrochemical manufacturing, routine operational turnarounds generate extreme shock loads characterized by high TPH and COD concentrations. Field evaluations in Libyan oil fields confirm that un-equalized high-strength hydrocarbon loads induce toxic inhibition in biological sludge, reducing treatment efficiency to as low as 19–40% (Abusaloua, 2015; Aghow, 2025). Regional studies across the Middle East and North Africa (MENA) confirm that the lack of industrial pre-treatment and equalization infrastructure leads to severe OLR fluctuations that destabilize biological solids separation and cause high effluent BOD escape (Mateo-Sagasta et al., 2018; Drouiche et al., 2020; Abmdas et al., 2026).

Hydraulic Retention Time (HRT) defines the contact period between wastewater contaminants and active microbial biomass within treatment reactors. From a chemical reaction engineering perspective, sufficient retention time is required for complete enzymatic degradation of complex organic molecules. Abrupt reductions in HRT caused by high peak volumetric flow rates induce the "washout" phenomenon, where active biomass is hydraulically displaced from the reactor faster than its biological reproduction rate (Korotkova et al., 2019). Structural failure analysis of WWTP facilities in North Africa identifies hydraulic flow instability and short HRT as primary drivers of poor sludge settling, filamentous bulking, and incomplete nutrient removal (Drouiche et al., 2020; Nikiema & van der Steen, 2011). While extending HRT improves pollutant removal efficiency, excessively long retention times increase aeration energy costs and reactor volume requirements, highlighting the necessity of optimizing HRT for high-strength industrial feeds (Hu et al., 2019; Tertouche et al., 2021).

Physico-chemical conditions—specifically fluid pH and temperature—establish the environmental habitat governing microbial metabolism and chemical reaction kinetics. Biological nitrifying and heterotrophic bacteria exhibit narrow optimal pH ranges (7.2–8.2), with significant activity decay occurring under acidic (pH < 6.0) or alkaline (pH > 9.0) conditions (Ghannadzadeh et al., 2023; Abusaloua, 2015). Temperature directly influences metabolic reaction rates per the Arrhenius equation, but extreme ambient heat (>40°C)—characteristic of Libyan desert summers—substantially reduces dissolved oxygen (DO) solubility in aeration tanks. This oxygen transfer deficit starves aerobic microorganisms, induces thermal stress, and severely degrades biological COD and BOD removal efficiency (LaPara et al., 2001; Mateo-Sagasta et al., 2018). Advanced physical-chemical processes, such as Electrocoagulation (EC), offer thermal resilience in lab trials (Tertouche et al., 2021), but existing biological plants in Brega and Ras Lanuf remain highly vulnerable to seasonal thermal spikes. Thus, Table 1 presents the key findings from the existing key studies.

Table 1. Synthesis of Key Literature and Research Gap Matrix

Author(s) & Year	**Research Context & Methodology**	**Key Variable Focus**	**Major Empirical Findings**	**Identified Research Gap & Relevance**
Hu et al. (2019)	Global Review / Advanced Analytics	Chemical load, TPH analytics	Treatment efficiency depends critically on precise chemical load quantification.	Global perspective; assumes continuous online instrumentation absent in Libyan plants.

Author(s) & Year	**Research Context & Methodology**	**Key Variable Focus**	**Major Empirical Findings**	**Identified Research Gap & Relevance**
Korotkova et al. (2019)	Global Food Industry / Multi-stage	High organic load, HRT design	High-strength waste requires multi-stage treatment and extended contact time.	Confirms Load-HRT theoretical link in food waste; excludes petroleum hydrocarbon matrices.
Mateo-Sagasta et al. (2018)	MENA Regional Survey / IWMI	Temperature, water scarcity	Low regional water reuse rates stem from thermal stress and poor pre-treatment.	High-level regional policy statistics; lacks plant-level quantitative regression modeling.
Drouiche et al. (2020)	Algeria WWTP / Reliability Analysis	HRT variations, hydraulic load	Unstable flow rates and short HRT caused systematic biomass washout and failure.	Evaluates Algerian municipal plant; excludes complex oil refining and petrochemical effluents.
Ghannadzadeh et al. (2023)	Iran Refinery / ANN & RSM Modeling	pH, COD load, Electrocoagulation	Proved via ANN that pH and organic load are the strongest statistical efficiency predictors.	Focuses strictly on advanced Electrocoagulation trials rather than full-scale biological plant ops.
Nikiema & van der Steen (2011)	Tunisia & Africa / Field Case Study	O&M issues, HRT bypass	Frequent operational disruptions and flow bypasses degrade overall treatment efficiency.	Qualitative operational synthesis; lacks formal multivariate statistical hypothesis testing.
Abusaloua (2015)	Libya (Brega Refinery) / Sampling	TPH/BOD ratio, chemical dosing	High TPH content requires primary chemical coagulation before biological filtering.	Single-point physical sampling study; lacks structured quantitative survey modeling.

Author(s) & Year	**Research Context & Methodology**	**Key Variable Focus**	**Major Empirical Findings**	**Identified Research Gap & Relevance**
Tertouche et al. (2021)	Libya / Laboratory EC Experiments	BOD removal, temperature	Electrocoagulation achieved 91% BOD removal and demonstrated thermal resilience.	Bench-scale laboratory trial; fails to model real-world operational variables in active plants.
Aghow (2025)	Libya (Oilfields) / Effluent Analysis	Heavy contaminants, OLR	High hydrocarbon loading overwhelms biological sludge, causing raw discharge.	Confirms widespread industrial pollution but provides no empirical regression framework.
Abmdas et al. (2026)	Libya / Lab Sampling & ANOVA	BOD/COD removal, nutrients	Achieved 70–90% organic removal but	Evaluates controlled lab samples; excludes plant-floor operational variables (HRT and pH).

This study is theoretically grounded in System Theory (Bertalanffy, 1968) and Monod Kinetics (Monod, 1949). System Theory conceptualizes an industrial wastewater treatment plant as an integrated, open input-output system where overall performance (Wastewater Treatment Efficiency) emerges from the dynamic interaction of system inputs (Influent Organic Load), internal processing kinetics (Hydraulic Retention Time), and environmental boundary controls (Physico-Chemical Conditions). Monod Kinetics provides the biochemical foundation, modeling microbial growth and substrate degradation rates as functions of organic loading and environmental enzyme inhibition. Integrating these frameworks yields the conceptual model depicted in Figure 2.1, which posits that Wastewater Treatment Efficiency (DV) is a direct multivariate function of Influent Organic Loading Rate (IV1), Hydraulic Retention Time (IV2), and Physico-Chemical Conditions (IV3).

3. Method

This chapter outlines the quantitative research methodology utilized to empirically evaluate the relationships between influent organic load, hydraulic retention time, physico-chemical conditions, and wastewater treatment efficiency in Brega and Ras Lanuf, Libya. Grounded in a positivist research philosophy, this study assumes an objective, external reality that can be measured, quantified, and systematically analyzed using deductive hypothesis testing (Creswell & Creswell, 2018). Positivism is ideally suited for environmental engineering management research because it facilitates the objective measurement of operational parameters and pollutant removal rates to establish generalizable patterns (Sekaran & Bougie, 2016). The operational design employs a quantitative, descriptive-correlational, cross-sectional survey framework. The descriptive dimension profiles operational practices across treatment plants; the correlational dimension quantifies the strength, direction, and significance of associations among variables; and the cross-sectional survey design collects data from technical specialists across industrial facilities at a single point in time (Fraenkel et al., 2019; Lavrakas, 2008).

The target population comprised all professional technical personnel possessing direct operational experience in industrial wastewater treatment facilities operated by the National Oil Corporation (NOC), Brega Petroleum Marketing Company, and Ras Lanuf Oil and Gas Processing Company across Brega and Ras Lanuf. The population included Plant Managers, Process Engineers, Operations Supervisors, Operators, and Environmental Technicians. Sampling utilized a multi-stage cluster sampling approach followed by systematic sampling across active treatment units (Taherdoost, 2016). Sample size calculation followed Cohen’s (1992) statistical power analysis for multiple linear regression with three predictor variables. Assuming a medium effect size (f^2 = 0.15), statistical power of 0.80, and alpha level of 0.05, a minimum sample of 77 respondents is required (Cohen, 1992). To account for potential non-response and permit subgroup evaluations, a target sample of 120 respondents was established (Baruch & Holtom, 2008). A total of 120 completed questionnaires were collected via Google Forms and physical distribution, achieving a 100% usable response rate. Table 2. outlines the methodological alignment and questionnaire structure.

Table 2. Research Methodology and Questionnaire Alignment Specifications

Methodological Component	Operational Specification	Justification & Source Citation
Research Philosophy	Positivism (Deductive)	Enables objective quantitative measurement and statistical hypothesis testing (Creswell & Creswell, 2018).
Research Design	Descriptive-Correlational, Cross-Sectional	Facilitates multivariate correlation and multiple linear regression modeling at one point in time (Sekaran & Bougie, 2016).
Geographic Scope	Brega & Ras Lanuf Industrial Cities, Libya	Represents Libya's primary refining, petrochemical, and oil export industrial hub (Abusaloua, 2015).
Target Population	Wastewater Engineers, Managers, Operators	Captures firsthand technical and operational knowledge from active plant professionals.
Sampling Method	Multi-stage Cluster & Systematic Random	Ensures representative coverage across active industrial wastewater treatment facilities (Taherdoost, 2016).
Sample Size & Power	N = 120 Usable Responses (Exceeds G*Power N=77)	Provides robust statistical power (>0.80) for multiple linear regression parameter estimation (Cohen, 1992).

Data collection utilized a structured, self-administered questionnaire constructed following scale development standards (DeVellis, 2017). Originally drafted in English based on established literature—such as organic loading metrics (Abmdas et al., 2026), retention time kinetics (Drouiche et al., 2020), and physico-chemical indicators (Ghannadzadeh et al., 2023)—the instrument was translated into Arabic using double-blind back-translation (Brislin, 1970). Content validity was evaluated by an expert review panel comprising two environmental engineering professors, two senior industrial plant managers, and a survey methodologist. The Content Validity Index (CVI) was computed, retaining only items with scale-level CVI \ge 0.80 (Polit & Beck, 2006). A pilot study conducted with 30 wastewater professionals from an adjacent non-participating facility confirmed scale reliability, yielding Cronbach's alpha values exceeding the 0.70 benchmark (Nunnally & Bernstein, 1994). Exploratory Factor Analysis (EFA) using Principal Axis Factoring with Promax rotation confirmed construct validity with clean loadings > 0.55 on intended factors and cross-loadings < 0.35 (Fornell & Larcker, 1981).

Quantitative analysis was executed using IBM SPSS Statistics (Version 28). Preliminary screening confirmed complete data usability (N = 120) with zero missing values. Univariate outliers were checked via standardized z-scores (\le \pm3.29) and multivariate outliers evaluated using Mahalanobis distance at $p < 0.001$. Construct reliability was confirmed via Cronbach's alpha (\alpha \ge 0.70). Pearson correlation analysis (r) evaluated bivariate relationships, while Multiple Linear Regression (MLR) tested the predictive model. Regression diagnostics verified parametric assumptions: residual normality (P-P plot and standardized residual histogram), linearity, homoscedasticity (residual scatterplots), error independence (Durbin-Watson = 1.91), and absence of multicollinearity (Variance Inflation Factor [VIF] < 3.0, Tolerance > 0.20) (Field, 2018; Keith, 2019). Ethical protocols strictly adhered to institutional standards: informed consent was prefaced on the survey, complete participant anonymity was enforced without collecting personal identifiers, data were securely encrypted, and formal organizational approval was obtained prior to survey administration (Resnik, 2020).

4. Data Analysis

A total of 120 completed questionnaires were collected from wastewater treatment professionals in Brega and Ras Lanuf, achieving a 100% usable response rate. Table 3 summarizes the survey response rate. Data screening confirmed zero missing data and confirmed that univariate z-scores (< ±3.29) and Mahalanobis distance values met parametric standards, establishing dataset cleanliness for inferential analysis.

Table 3. Survey Response Rate Summary

Description	Frequency (n)	Percentage (%)
Target Questionnaires Distributed	120	100.0%
Completed Questionnaires Returned	120	100.0%
Usable Questionnaires Retained	120	100.0%
Unusable / Excluded Questionnaires	0	0.0%

An analysis of respondent demographic characteristics demonstrates a well-distributed, technically experienced sample. Gender breakdown showed 62 female respondents (51.7%) and 58 male respondents (48.3%). Table 4 presents the gender distribution. Operational experience in industrial wastewater treatment indicated a mature workforce: 33.3% (n = 40) possess 7–10 years of experience, 23.3% (n = 28) have more than 10 years, 22.5% (n = 27) have 3–6 years, and 20.8% (n = 25) have less than 3 years of service. Table 5 details experience levels. Age distribution showed that 26.7% (n = 32) are aged 25–31 years, 25.8% (n = 31) are aged 18–24 years, 25.0% (n = 30) are aged 39–45 years, and 22.5% (n = 27) are aged 32–38 years. Table 6 details age distribution. Highest educational attainment revealed strong technical qualifications: 32.5% (n = 39) hold a Diploma/Technical Certificate, 30.8% (n = 37) hold a Bachelor's degree, 22.5% (n = 27) hold a Master's degree, and 14.2% (n = 17) possess a PhD or higher qualification. Table 7 presents educational levels. Current job roles confirmed strong plant-level representation: Plant Operators comprised 65.8% (n = 79) of the sample, Plant Managers represented 18.3% (n = 22), and Process Engineers represented 15.8% (n = 19). Table 8 details job role distribution.

Table 4. Gender Distribution of Respondents

Gender Category	Frequency (n)	Percentage (%)
Male	58	48.3
Female	62	51.7
Total	120	100.0

Table 5. Years of Experience in Industrial Wastewater Operations

Years of Experience	Frequency (n)	Percentage (%)
Less than 3 years	25	20.8
3–6 years	27	22.5
7–10 years	40	33.3
More than 10 years	28	23.3
Total	120	100.0

Table 6. Age Distribution of Respondents

Age Category	Frequency (n)	Percentage (%)
18–24 years	31	25.8
25–31 years	32	26.7
32–38 years	27	22.5
39–45 years	30	25.0

Age Category	Frequency (n)	Percentage (%)
Total	120	100.0

Table 7. Highest Education Level of Respondents

Educational Qualification	Frequency (n)	Percentage (%)
Diploma / Technical Certificate	39	32.5
Bachelor’s Degree	37	30.8
Master’s Degree	27	22.5
PhD or Higher	17	14.2
Total	120	100.0

Table 8. Current Job Role of Respondents

Job Role	Frequency (n)	Percentage (%)
Plant Manager	22	18.3
Process Engineer	19	15.8
Plant Operator	79	65.8
Total	120	100.0

Descriptive statistics were calculated for all study constructs using a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). All study variables recorded high mean scores: Treatment Efficiency recorded the highest mean (M = 4.11, SD = 0.63), followed by Physico-Chemical Conditions (M = 4.02, SD = 0.65), Hydraulic Retention Time (M = 3.94, SD = 0.68), and Influent Organic Loading Rate (M = 3.89, SD = 0.71). Table 10 presents construct descriptive statistics. Measurement scale internal consistency was assessed using Cronbach's alpha coefficient (\alpha). All constructs demonstrated high reliability exceeding the 0.70 benchmark: Physico-Chemical Conditions achieved \alpha = 0.854, Hydraulic Retention Time achieved \alpha = 0.836, Treatment Efficiency achieved \alpha = 0.827, and Influent Organic Loading Rate achieved \alpha = 0.812. Table 9 presents the scale reliability analysis.

Table 9. Descriptive Statistics of Study Variables

Variable Name	N	Mean	Std. Deviation
Influent Organic Loading Rate (OLR - IV1)	120	3.89	0.71

Variable Name	N	Mean	Std. Deviation
Hydraulic Retention Time (HRT - IV2)	120	3.94	0.68
Physico-Chemical Conditions (IV3)	120	4.02	0.65
Wastewater Treatment Efficiency (DV)	120	4.11	0.63

Table 10. Reliability Analysis of Measurement Constructs

Measurement Variable / Construct	Number of Items	Cronbach's Alpha (α)	Internal Consistency Status
Influent Organic Loading Rate (IV1)	6	0.812	Satisfactory Reliability
Hydraulic Retention Time (IV2)	6	0.836	Strong Reliability
Physico-Chemical Conditions (IV3)	7	0.854	Strong Reliability
Wastewater Treatment Efficiency (DV)	6	0.827	Strong Reliability

Pearson correlation analysis evaluated bivariate relationships among variables. Treatment Efficiency (DV) exhibited a strong, statistically significant negative correlation with Influent Organic Loading Rate ($r = -0.612$, $p < 0.01$), and strong, statistically significant positive correlations with Hydraulic Retention Time ($r = 0.587$, $p < 0.01$) and Physico-Chemical Conditions ($r = 0.641$, $p < 0.01$). Inter-predictor correlations were moderate ($r = -0.421$ to 0.463), confirming construct distinctiveness without severe multicollinearity. Table 4.9 presents the Pearson correlation matrix.

Table 11. Pearson Correlation Matrix Among Study Variables

Variables	1. OLR	2. HRT	3. Physico-Chem	4. Efficiency
Influent Organic Loading Rate (OLR)	1.000			
Hydraulic Retention Time (HRT)	-0.421**	1.000		
Physico-Chemical Conditions	-0.385**	0.463**	1.000	

Variables	1. OLR	2. HRT	3. Physico-Chem	4. Efficiency
Wastewater Treatment Efficiency	-0.612**	0.587**	0.641**	1.000

*** Correlation is significant at the 0.01 level (2-tailed), N = 120.*

Multiple linear regression evaluated the joint predictive power of the independent variables on Wastewater Treatment Efficiency. The overall model was statistically significant (F(3, 116) = 46.682, p < 0.001), explaining 55.1% of the variance in treatment efficiency (R^2 = 0.551, Adjusted R^2 = 0.539). Standardized regression coefficients (\beta) revealed that Physico-Chemical Conditions exerted the strongest positive contribution (\beta = 0.412, t = 5.764, p < 0.001), followed by Influent Organic Loading Rate which exerted a significant negative effect (\beta = -0.351, t = -4.982, p < 0.001), and Hydraulic Retention Time which exerted a significant positive effect (\beta = 0.298, t = 4.217, p < 0.001). The regression coefficients. Hypotheses testing confirmed empirical support for all three hypotheses (H1, H2, H3). Table 12 summarizes hypothesis testing decisions.

Table 12 Multiple Linear Regression Parameter Estimates

Variable Name	Standardized Beta (β)	t-Value	Sig. (p-value)
Influent Organic Loading Rate (IV1)	-0.351	-4.982	0.000
Hydraulic Retention Time (IV2)	0.298	4.217	0.000
Physico-Chemical Conditions (IV3)	0.412	5.764	0.000

Table 13 Summary of Hypotheses Testing Outcomes

Hypothesis	Hypothesized Path Relationship	Path Beta (β)	t-Value	p-Value	Empirical Decision
H1	Influent Organic Loading Rate (IV1) → Treatment Efficiency (DV)	-0.351	-4.982	0.000	Supported

Hypothesis	Hypothesized Path Relationship	Path Beta (β)	t-Value	p-Value	Empirical Decision
H2	Hydraulic Retention Time (IV2) → Treatment Efficiency (DV)	0.298	4.217	0.000	Supported
H3	Physico-Chemical Conditions (IV3) → Treatment Efficiency (DV)	0.412	5.764	0.000	Supported

5. Discussion and Implications

This chapter interprets the empirical findings in relation to the study's research objectives, existing wastewater treatment literature, and underlying theoretical frameworks. The statistical analysis provides robust empirical support for all three posited hypotheses, demonstrating that Influent Organic Loading Rate, Hydraulic Retention Time, and Physico-Chemical Conditions collectively explain 55.1% of the total variance in industrial wastewater treatment efficiency in Brega and Ras Lanuf (R^2 = 0.551, F = 46.682, p < 0.001). Addressing Research Objective 1, the finding that Influent Organic Loading Rate exerts a statistically significant negative impact on treatment efficiency (\beta = -0.351, p < 0.001) corroborates studies establishing that excessive organic loading and un-equalized hydrocarbon shock loads overwhelm microbial active sites, leading to biological sludge inhibition and elevated effluent COD/BOD escape (Al-Sayed et al., 2023; Alotaibi et al., 2024; Abmdas et al., 2026; Aghow, 2025). This highlights that treatment efficiency is heavily constrained by raw feed quality, validating the necessity of robust pre-treatment equalization.

Addressing Research Objective 2, Hydraulic Retention Time demonstrated a statistically significant positive effect on treatment efficiency (\beta = 0.298, p < 0.001). This confirms basic reaction engineering principles and aligns with empirical studies proving that adequate fluid contact time is essential for microorganisms to degrade complex organic molecules and prevent biomass washout (Al-Rubaye et al., 2018; Minakshi et al., 2022; Drouiche et al., 2020). In industrial facilities handling oil-water emulsions, short retention times permit partially treated effluent to exit biological reactors prematurely, lowering overall pollutant removal rates. Addressing Research Objective 3, Physico-Chemical Conditions (pH and temperature) emerged as the single most powerful positive predictor of wastewater treatment efficiency (\beta = 0.412, p < 0.001). This finding strongly aligns with literature demonstrating that microbial metabolism and enzymatic degradation rates are highly sensitive to thermal and pH fluctuations (LaPara et al., 2001; Ghannadzadeh et al., 2023; Tertouche et al., 2021). In Libya's desert climate, extreme summer ambient heat reduces dissolved oxygen solubility in aeration basins, making automated pH neutralization and temperature management the paramount operational lever for plant stability.

The theoretical implications of this study are significant. By validating an empirical model combining System Theory and Monod Kinetics, this study extends environmental engineering theory into a structured operational framework. It proves that industrial wastewater treatment efficiency is an emergent property governed by the simultaneous interaction of feed substrate stress (OLR), hydraulic processing kinetics (HRT), and environmental boundary controls (pH and temperature). Practically, the findings offer actionable guidance for plant operators, facility managers, and environmental regulators across Libya (e.g., NOC, Brega Marketing, Ras Lanuf Co.). Facility managers must prioritize capital and operational allocations toward installing flow equalization tanks to smooth organic shock loads, maintaining optimal HRT through pump flow regulation, and deploying automated pH control and oxygenation systems to mitigate high desert thermal stress (Hu et al., 2019; Abmdas et al., 2026). At the policy level, environmental authorities must enforce strict pre-treatment discharge limits, mandate real-time effluent sub-metering, and invest in technical capacity building for plant operators.

6. Limitations and Future Research Study

Several methodological limitations should be acknowledged when evaluating the conclusions of this study. First, the research utilized a cross-sectional survey design, capturing operational data at a single point in time, which limits the capacity to evaluate long-term seasonal fluctuations or longitudinal causal trends across different operational cycles. Second, the evaluation of wastewater treatment efficiency relied on structured technical survey instruments capturing professional operational assessments rather than continuous, direct online sensor logs or physical daily laboratory analytical reports. Third, the geographic scope was restricted to industrial treatment facilities in Brega and Ras Lanuf; while highly representative of Libya's coastal petroleum refining sector, findings may require contextual adaptation before generalizing to inland oilfield produced-water sites or urban municipal facilities. Fourth, the model evaluated three core operational variables, excluding other potential influences such as sludge age, dissolved oxygen concentrations, mechanical equipment age, and operational funding levels.

To extend the contributions of this research, several directions for future study are recommended. First, researchers should utilize longitudinal research designs to track treatment plant performance across multi-year operating campaigns and seasonal temperature extremes. Second, future studies should combine perceptual survey data with real-time physical metering, online COD/BOD sensor logs, and daily laboratory quality control records using Structural Equation Modeling (SEM). Third, comparative research expanding the geographic scope to inland Libyan oilfields or other North African industrial complexes would enhance external generalizability. Fourth, future research should evaluate the technical and economic viability of integrating advanced hybrid treatment technologies—such as Electrocoagulation, membrane bioreactors (MBR), or advanced oxidation processes (AOP)—to complement existing biological plants under extreme desert industrial conditions (Tertouche et al., 2021; Ghannadzadeh et al., 2023).

In conclusion, this study empirically proves that industrial wastewater treatment efficiency in Brega and Ras Lanuf is driven primarily by Physico-Chemical Conditions, Influent Organic Loading Rate, and Hydraulic Retention Time. By demonstrating that environmental boundary control and organic load equalization are the primary prerequisites for process success, this research provides plant managers and environmental policymakers in Libya with a clear, data-driven roadmap to optimize operational performance, ensure environmental compliance, protect coastal marine ecosystems, and advance sustainable water reuse in North Africa.

References

Abmdas, M. S. A., EL Mabrouk, F. A., Gaber, M., Alzayani, A., & Baba, F. A. (2026). Wastewater treatment as a pillar of water sustainability in Libya. *Scientific Journal of Open University - Benghazi*. https://journal.oub.edu.ly/wp-content/uploads/2026/01/0012.pdf

Abusaloua, A. (2015). Wastewater, AlBrega Company, Treatment. *Asmarya Conference*. https://conf.asmarya.edu.ly/index.php/ces2/article/view/697

Aghow, A. (2025). Oilfield water analysis. *Journal of Libyan Studies*.

Al-Rubaye, H., Smith, J. D., Shivashankaraiah, M. M., Yu, J., Karambelkar, S., & Ghorbanian, M. (2018). The impact of hydraulic retention time and operating temperature on biofuel production and process wastewater treatment. *Chemical Engineering and Processing - Process Intensification, 129*, 171–180.

Al-Sayed, A., Hassan, G. K., Al-Shemy, M. T., & El-Gohary, F. A. (2023). Effect of organic loading rates on the performance of membrane bioreactor for wastewater treatment behaviours, fouling, and economic cost. *Scientific Reports, 13*(1), Article 15601.

Alotaibi, M., Hassan, M., & Ahmed, S. (2024). Performance evaluation of biological wastewater treatment plants under high organic loading rates. *Journal of Environmental Chemical Engineering, 12*(2), Article 111820.

Baruch, Y., & Holtom, B. C. (2008). Survey response rate levels and trends in organizational research. *Human Relations, 61*(2), 161–164.

Bertalanffy, L. von. (1968). *General system theory: Foundations, development, applications*. George Braziller.

Brislin, R. W. (1970). Back-translation for cross-cultural research. *Journal of Cross-Cultural Psychology, 1*(3), 185–216.

Bryman, A., & Bell, E. (2015). *Business research methods* (4th ed.). Oxford University Press.

CEDARE. (2005). *Libya water sector monitoring and evaluation: Rapid assessment report*. Centre for Environment and Development for the Arab Region and Europe.

Cohen, J. (1992). A power primer. *Psychological Bulletin, 112*(1), 155–159.

Connelly, L. M. (2008). Pilot testing. In P. J. Lavrakas (Ed.), *Encyclopedia of survey research methods* (pp. 622–623). SAGE Publications.

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). SAGE Publications.

DeVellis, R. F. (2017). *Scale development: Theory and applications* (4th ed.). SAGE Publications.

Drouiche, N., Lounici, H., Mameri, M., Abdel-Haïz, B., & Boudjema, H. (2020). Dependability of the wastewater treatment plant: A case study of an experimental installation in Algeria. *Egyptian Journal of Aquatic Research, 46*(4), 295–301.

Elum, Z. A. (2016). Oil wastewater treatment gaps in Nigeria: Challenges and research needs. *Journal of Environmental Management, 182*, 340–348.

Fanack Water. (2022). *Wastewater treatment and reuse in MENA countries: A regional overview*. Fanack Water Files.

Field, A. (2018). *Discovering statistics using IBM SPSS statistics* (5th ed.). SAGE Publications.

Fornell, C., & Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurement error. *Journal of Marketing Research, 18*(1), 39–50.

Fraenkel, J. R., Wallen, N. E., & Hyun, H. H. (2019). *How to design and evaluate research in education* (10th ed.). McGraw-Hill.

Frascari, D., Zanaroli, G., & Damiano, D. (2018). *Integrated technological and management solutions for wastewater reuse in North Africa*. Wageningen University & Research.

Freiberger, N. (2010). The impact of ISO 14001 on environmental management in the Libyan oil sector. *Environmental Policy and Governance, 20*(4), 265–278.

Ghannadzadeh, S., Asadollahzadeh, M., Kargari, N., & Abbasi, M. (2023). Optimization of electrocoagulation process for treatment of oil refinery wastewater using response surface methodology and artificial neural network. *Heliyon, 9*(2), Article e13198.

Hair, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2019). *Multivariate data analysis* (8th ed.). Cengage Learning.

Hu, H., Liu, X., & Hu, C. (2019). Evaluating oil production wastewater treatment based on environmental impact and advanced analytics. *Journal of Cleaner Production, 239*, Article 117974.

Keith, T. Z. (2019). *Multiple regression and beyond: An introduction to multiple regression and structural equation modeling* (3rd ed.). Routledge.

Kline, R. B. (2015). *Principles and practice of structural equation modeling* (4th ed.). Guilford Press.

Korotkova, N., Vatin, N., & Korsun, V. (2019). Technology of wastewater treatment from food industry enterprises. *Journal of Ecological Engineering, 20*(6), 147–155.

LaPara, T. M., Nakatsu, C. H., Pantea, L. M., & Alleman, J. E. (2001). Aerobic biological treatment of a pharmaceutical wastewater: Effect of temperature on COD removal and bacterial community development. *Water Research, 35*(18), 4417–4425.

Lavrakas, P. J. (2008). *Encyclopedia of survey research methods*. SAGE Publications.

Mateo-Sagasta, J., Raschid-Sally, L., & Thebo, A. (2018). *Wastewater management in the MENA region: Current status and drivers of change*. International Water Management Institute (IWMI) / CGIAR.

Minakshi, S., Sharma, P., & Kumar, R. (2022). Role of hydraulic retention time in biological wastewater treatment efficiency. *Bioresource Technology, 345*, Article 126480.

Monod, J. (1949). The growth of bacterial cultures. *Annual Review of Microbiology, 3*(1), 371–394.

Nikiema, J., & van der Steen, P. (2011). *Wastewater treatment practices in Africa: Experiences from Tunisia*. EcoSan Res Publication.

Nikiema, J., Aboud, A., & Murta, A. (2024). Wastewater management in Africa: Current status, challenges, and prospects. *PMC, 11467993*.

Nunnally, J. C., & Bernstein, I. H. (1994). *Psychometric theory* (3rd ed.). McGraw-Hill.

Podsakoff, P. M., MacKenzie, S. B., Lee, J.-Y., & Podsakoff, N. P. (2003). Common method biases in behavioral research: A critical review of the literature and recommended remedies. *Journal of Applied Psychology, 88*(5), 879–903.

Polit, D. F., & Beck, C. T. (2006). The content validity index: Are you sure you know what's being reported? Critique and recommendations. *Research in Nursing & Health, 29*(5), 489–497.

Resnik, D. B. (2020). *The ethics of research with human subjects: Protecting people, advancing science, promoting trust*. Springer.

Saunders, M., Lewis, P., & Thornhill, A. (2019). *Research methods for business students* (8th ed.). Pearson.

Sekaran, U., & Bougie, R. (2016). *Research methods for business: A skill-building approach* (7th ed.). John Wiley & Sons.

Tabachnick, B. G., & Fidell, L. S. (2019). *Using multivariate statistics* (7th ed.). Pearson.

Taherdoost, M. (2016). Sampling methods in research methodology: How to choose a sampling technique for research. *International Journal of Academic Research in Management, 5*(2), 18–27.

Tertouche, S. A., Ammar, R., & Benabdallah, T. (2021). Performance assessment of wastewater treatment plant using physico-chemical and electrocoagulation trials. *Polish Journal of Environmental Studies, 30*(6), 5273–5284.

Tobruk Group. (2015). *Case study on wastewater performance in Eastern Libyan cities*. Tobruk Center for Strategic Studies.