

Wastewater Treatment Plant Performance Evaluation and Effluent Reuse Potential: A Case Study of the Ramshar WWTP

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Received: 05 September 2025

Accepted: 06 October 2025

Available online: 03 December 2025

Abstract: This study presents a comprehensive evaluation of the Ramshar Wastewater Treatment Plant (WWTP) and assesses the suitability of its treated effluent for agricultural and green space irrigation applications. Five physicochemical water quality parameters—biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), total suspended solids (TSS), electrical conductivity (EC), and pH—were monitored over a 12-month period and analyzed through an integrated framework combining descriptive statistics, regulatory compliance assessment, and probabilistic risk modeling using a 100,000-iteration Monte Carlo simulation. The treated effluent demonstrated stable and favorable quality characteristics, with mean concentrations of 34.83 mg/L (BOD₅), 55.83 mg/L (COD), 16.83 mg/L (TSS), 500 µS/cm (EC), and a pH of 7.82—all substantially below the corresponding national limits for agricultural irrigation under Iranian Standard No. 2901. Full compliance (100%) with agricultural reuse standards was achieved across all monitored parameters. For green space irrigation, all parameters except BOD₅ consistently satisfied the more stringent regulatory thresholds. While COD, TSS, EC, and pH exhibited zero probability of exceedance in the Monte Carlo simulation, BOD₅ displayed a 19.41% probability of exceeding the 40 mg/L limit, reflecting moderate seasonal and operational sensitivity inherent to the biological treatment process. Notwithstanding this variability, overall effluent quality remained within acceptable ranges for landscape irrigation under most operational conditions. The integration of deterministic and probabilistic analytical approaches provides a robust understanding of effluent reliability, underscoring the WWTP's strong performance and operational stability. The findings confirm that the Ramshar WWTP constitutes a dependable source of reclaimed water for agricultural irrigation, with generally favorable potential for green space reuse, and indicate that targeted optimization of biological oxygen demand removal could further enhance compliance under stringent reuse criteria.

Keywords: Wastewater treatment; Effluent reuse; Monte Carlo simulation; Electrical conductivity; Probabilistic risk assessment.

1. Introduction

The intensification of global water scarcity constitutes one of the most pressing environmental and socioeconomic challenges confronting the twenty-first century. Recent assessments by the World Meteorological Organization indicate that five consecutive years of below-normal river flows and reservoir inflows have imposed unprecedented stress on global freshwater systems, with an estimated 3.6 billion people currently experiencing water shortages—a figure projected to surpass five billion by 2050 [1]. The 2024 United Nations World Water Development Report further documents that approximately half of the global population endures severe water scarcity for at least one month annually, while agriculture accounts for approximately 72% of all freshwater withdrawals worldwide [2]. When a territory withdraws 25% or more of its renewable freshwater resources, it enters a condition of water stress—a threshold already exceeded by five of eleven major world regions [3]. These converging pressures, compounded by accelerating climate change, rapid urbanization, and demographic growth, have elevated treated wastewater reuse from a supplementary measure to a strategic necessity within integrated water resource management frameworks [4, 5].

Iran epitomizes the acute vulnerability of arid nations to freshwater depletion. With mean annual precipitation

of approximately 250 mm—roughly one-third of the global average—and evaporation rates exceeding 2,000 mm per year, approximately 90% of Iran's territory is classified as arid or semi-arid [6]. The 2024–2025 hydrological year has been characterized as one of the most critical in recorded history, with national average rainfall approximately 45% below normal, nineteen provinces experiencing significant drought, and Tehran's five principal reservoirs holding only 13% of capacity as of early 2025. Iran's national groundwater reserves declined by approximately 211 ± 34 km³ between 2003 and 2019—more than twice the country's annual water consumption [7]. Agriculture, which consumes over 90% of national water resources while contributing only 9% of gross domestic product, exacerbates this crisis through inefficient flood irrigation practices and heavily subsidized water pricing structures [8]. Under these circumstances, the reuse of treated municipal wastewater has emerged as a critical policy priority, with national targets aiming to increase effluent reuse from 25% to 70% of treated volumes by 2030 [9].

The utilization of treated wastewater for agricultural and landscape irrigation has been extensively demonstrated as both technically feasible and economically advantageous, particularly in water-scarce regions. Contemporary reviews confirm that reclaimed water can effectively supplement or replace freshwater

in irrigation schemes while simultaneously reducing external nutrient inputs and alleviating pressure on surface and groundwater resources [10, 11]. In arid and semi-arid contexts, decentralized wastewater treatment systems designed for agricultural reuse have demonstrated considerable promise, achieving BOD₅ removal efficiencies exceeding 90% even under high-strength influent conditions [12]. Concurrently, effluent reuse without rigorous quality assessment exposes receiving environments and public health to significant risks, reinforcing the imperative for systematic performance monitoring and probabilistic risk evaluation [13, 14].

Wastewater treatment plant (WWTP) performance evaluation is fundamental to ensuring that effluent quality satisfies established reuse criteria and environmental discharge standards. Five key physicochemical parameters—five-day biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), total suspended solids (TSS), electrical conductivity (EC), and pH—collectively serve as primary compliance indicators across most national and international standards governing wastewater reuse [15, 16]. In activated sludge systems, which represent the most widely deployed secondary treatment technology globally, organic matter removal typically achieves 85–98% BOD₅ and 60–85% COD reduction under optimal operational conditions, although performance remains subject to variability driven by influent load fluctuations, hydraulic retention time, and microbial community dynamics [17]. Comprehensive assessments of full-scale WWTPs have increasingly emphasized the integration of statistical descriptors with graphical tools to characterize effluent variability, identify parameter-specific vulnerabilities, and support compliance decision-making [18, 19].

Seasonal variability constitutes one of the most operationally significant factors influencing WWTP performance. Temperature reductions during winter months suppress microbial metabolic rates, reduce oxygen transfer efficiency in aeration systems, and diminish sludge settleability, collectively impairing biological treatment performance [20]. Investigations of municipal activated sludge facilities operating across climatic gradients have demonstrated that seasonal fluctuations in BOD₅ removal efficiency of 10–25% are common, with summer–winter differentials frequently exceeding permissible effluent thresholds for sensitive reuse categories such as landscape irrigation [21, 22]. In arid regions, additional complexity arises from highly variable influent concentrations associated with low per capita water use, tourist influxes, and seasonal industrial inputs [12]. These dynamics underscore the inadequacy of evaluating WWTP performance solely through arithmetic mean concentrations and highlight the necessity of temporally resolved monitoring frameworks.

To address the inherent uncertainty in treatment performance and effluent quality, probabilistic risk assessment methodologies—particularly Monte Carlo simulation (MCS)—have gained widespread adoption as analytical tools for quantifying compliance probabilities under variable conditions. Monte Carlo approaches generate large statistical ensembles of possible effluent concentration realizations, derived from empirically fitted probability distributions, thereby enabling estimation of exceedance probabilities and regulatory non-compliance risk with greater rigor than deterministic point-estimate methods alone [23, 24]. Applications of MCS in water quality studies have extended from groundwater contamination risk assessment [25] to surface water pollution characterization [26] and hospital WWTP occupational exposure evaluation [27]. In the context of effluent reuse planning, MCS furnishes decision-makers with probabilistic compliance profiles that explicitly quantify the likelihood of parameter-specific exceedances relative to applicable standards—information essential for aligning treatment plant operations with risk-tolerant management thresholds [28, 29].

Despite extensive documentation of WWTP performance in the international literature, case-specific evaluations from Iranian treatment facilities remain comparatively limited, particularly those integrating both deterministic compliance analysis and probabilistic risk modeling under arid climatic conditions. Existing Iranian studies have addressed broad national trends in wastewater management policy [8], industrial estate reuse frameworks [30], and socio-behavioral dimensions of agricultural reuse adoption [9]; however, detailed quantitative assessments of individual municipal WWTPs—incorporating full seasonal resolution and probabilistic exceedance analysis—remain insufficiently represented in the peer-reviewed literature. This gap is particularly significant given Iran's critical water deficit, the expanding network of municipal treatment plants, and the strategic importance of maximizing the reuse potential of treated effluent as a reliable secondary water resource.

The present study addresses this knowledge gap through a comprehensive evaluation of the Ramshar New City Wastewater Treatment Plant, a municipal activated sludge facility serving the Ramshar New City development in the Sistan and Baluchestan Province of southeastern Iran. A 12-month monitoring dataset comprising five key quality parameters—BOD₅, COD, TSS, EC, and pH—was analyzed through a multi-method analytical framework combining: (i) descriptive statistical characterization of effluent quality and treatment efficiency; (ii) seasonal decomposition to identify temporal performance patterns; (iii) deterministic compliance assessment against Iranian national standards for agricultural and green space irrigation (Standard No. 2901); and (iv) probabilistic

risk modeling using a 100,000-iteration Monte Carlo simulation to quantify parameter-specific exceedance probabilities and overall compliance reliability. The specific objectives of this study are: to evaluate Ramshar WWTP performance with respect to key pollutant removal efficiency; to assess the potential of treated effluent for agricultural and landscape irrigation reuse; to quantify compliance probability and non-compliance risk under operational variability; and to propose targeted management strategies to enhance effluent suitability for sensitive reuse applications.

2. Materials and Methods

2.1. Study Area and Treatment Plant Description

The Ramshar New City Wastewater Treatment Plant (WWTP) is a full-scale municipal facility situated within the Ramshar New City urban development in Sistan and Baluchestan Province, southeastern Iran—one of the country's most arid regions, characterized by mean annual precipitation below 80 mm and pan evaporation rates exceeding 3,000 mm per year [6]. The plant is designed to treat domestic wastewater generated by the local urban population using conventional activated sludge (CAS) technology, a suspended-growth biological process widely recognized for its effectiveness in removing biodegradable organic matter and suspended solids from municipal wastewater [17, 18].

The treatment train comprises four sequential unit processes. In the preliminary treatment stage, influent wastewater passes through coarse and fine bar screens to remove large solids and floating debris, followed by a grit removal channel where inorganic particles such as sand, gravel, and grit are separated by gravitational settling and differential velocity. This stage protects downstream mechanical equipment from abrasion and prevents accumulation of inorganic material in biological treatment units [15, 31]. In the primary sedimentation stage, screened and de-gritted wastewater flows to primary clarifiers, where suspended solids undergo gravity settling with a hydraulic retention time of approximately two hours. Primary sludge collected at the base of the clarifier is removed for further processing, while the primary effluent—with significantly reduced organic load—advances to the biological treatment stage [12]. The biological treatment stage consists of aerated basins operating under aerobic conditions, where a diverse microbial community metabolizes dissolved and colloidal organic pollutants as carbon and energy sources. Operational parameters including mixed liquor suspended solids (MLSS) concentration, food-to-microorganism (F/M) ratio, dissolved oxygen (DO) concentration (target ≥ 2 mg/L), and hydraulic retention time (HRT) are monitored and controlled to optimize biological activity and effluent quality. Compressed air is supplied through fine-bubble diffusers installed at the tank base, providing both oxygen transfer and bulk mixing of the mixed liquor

[19]. In the secondary clarification stage, mixed liquor from the aeration basins flows to secondary clarifiers, where biological floc separates from treated effluent by gravity settling. Clarified supernatant is discharged as final effluent, a portion of the settled sludge—return activated sludge (RAS)—is recycled to the aeration basin inlet to maintain the required microbial population, and the remainder—waste activated sludge (WAS)—is withdrawn and directed to sludge handling facilities [18].

2.2. Monitoring Program and Analytical Procedures

A systematic effluent monitoring program was implemented over a continuous 12-month period (January through December) to capture the full spectrum of seasonal variability in treatment performance. Composite effluent samples were collected monthly from the plant's final discharge point, coinciding with average daily flow conditions to ensure representativeness. Samples were collected in pre-cleaned, high-density polyethylene (HDPE) containers, preserved according to parameter-specific protocols, and transported under refrigeration (4°C) to the laboratory for immediate analysis to minimize degradation [32].

Five key water quality parameters were determined using internationally standardized analytical procedures as defined in the 24th edition of Standard Methods for the Examination of Water and Wastewater [32]. Five-day biochemical oxygen demand (BOD₅) was determined using the dilution and seeding method (APHA Method 5210B) at $20 \pm 1^\circ\text{C}$ for a 5-day incubation period, quantifying the biodegradable organic matter fraction removable by microbial activity and serving as the primary indicator of biological treatment efficacy [21]. Chemical oxygen demand (COD) was measured by the closed reflux colorimetric method (APHA Method 5220C) using potassium dichromate as oxidant under acidic conditions at 150°C for 2 hours, capturing total oxidizable organic matter including both biodegradable and recalcitrant fractions [16]. Total suspended solids (TSS) were determined by filtration through a pre-weighed glass microfiber filter (nominal pore size 1.5 μm) and drying at $103\text{--}105^\circ\text{C}$ to constant mass per APHA Method 2540D, serving as a key indicator of solid-liquid separation efficacy in secondary clarification [18]. Electrical conductivity (EC) was measured using a calibrated conductivity meter with automatic temperature compensation to 25°C , serving as a surrogate measure of total dissolved solids and salinity—critical constraints on effluent suitability for irrigation of salt-sensitive crops and ornamental vegetation [12]. pH was determined immediately after sample collection using a temperature-compensated electrode pH meter calibrated with two-point standard buffer solutions (pH 4.0 and 7.0), as pH influences both biological treatment activity and compliance for all wastewater reuse categories [32].

All laboratory determinations were performed in triplicate to ensure analytical reproducibility. A rigorous quality assurance/quality control (QA/QC) protocol was maintained throughout the monitoring program, comprising instrument calibration checks prior to each analytical run, procedural blank analysis, certified reference material verification, and duplicate sample analysis with acceptance criteria of relative percentage difference (RPD) $\leq 10\%$ [32, 33].

2.3. Effluent Quality Standards and Evaluation Criteria

Effluent quality was evaluated against the Iranian National Standard for Wastewater Reuse in Agriculture and Green Spaces (Standard No. 2901), established by the Iranian Department of Environment (DOE). Two reuse categories with distinct permissible limits were considered, reflecting the differing sensitivity levels of receiving environments and potential exposure pathways [9, 34]. Class II (Agricultural Irrigation) is applicable to unrestricted irrigation of food and non-food crops, with relatively lenient thresholds reflecting the soil's natural buffering capacity and root zone dilution potential. Class III (Green Space Irrigation) is applicable to irrigation of public parks, urban green spaces, and landscaping, with more stringent thresholds accounting for potential direct human contact and aesthetic considerations such as odor prevention [10]. The specific regulatory limits and corresponding analytical methods are presented in Table 1.

Table 1. Regulatory limits for wastewater reuse (Iranian Standard No. 2901) and corresponding analytical methods.

Parameter	Agricultural (Class II)	Green Space (Class III)	Unit	APHA Method
BOD ₅	≤ 100	≤ 40	mg/L	5210B
COD	≤ 200	≤ 100	mg/L	5220C
TSS	≤ 100	≤ 40	mg/L	2540D
EC	≤ 2000	≤ 1500	$\mu\text{S}/\text{cm}$	Direct meter
pH	6.5–8.5	6.5–8.5	—	Direct meter

2.4. Data Analysis Framework

2.4.1. Descriptive Statistical Analysis

Descriptive statistics were calculated for each effluent quality parameter to characterize the central tendency, dispersion, and variability of the 12-month monitoring dataset. The arithmetic mean ($\bar{x}$), representing the expected value of parameter concentration under observed operating conditions, was computed as:

$$\bar{x} = (1/n) \sum_{i=1}^n X_i \quad (1)$$

where $\bar{x}$ is the sample mean, x_i represents the i^{th} individual observation, and n is the total number of observations ($n = 12$ monthly samples). The sample standard deviation, quantifying absolute dispersion of

individual observations around the mean, was computed as:

$$SD = \sqrt{\left[(1/(n-1)) \sum (x_i - \bar{x})^2 \right]} \quad (2)$$

where s is the sample standard deviation. Bessel's correction factor ($n-1$) was applied in the denominator to obtain an unbiased estimator of the population variance [35]. The coefficient of variation (CV), expressing relative variability as a dimensionless percentage, was determined as:

$$CV (\%) = (SD / \bar{x}) \times 100 \quad (3)$$

Minimum and maximum observed concentrations were recorded to establish the full range of observed values. CV values were classified as: low variability ($CV < 15\%$), moderate variability ($15\% \leq CV < 30\%$), and high variability ($CV \geq 30\%$), following established conventions for wastewater quality datasets [15].

2.4.2. Treatment Efficiency Calculation

Pollutant removal efficiencies for BOD₅, COD, and TSS were calculated to assess the overall performance of the treatment train. The removal efficiency (η) was determined using:

$$\eta (\%) = [(C_{in} - C_{out}) / C_{in}] \times 100 \quad (4)$$

where η represents the percentage removal efficiency, C_{in} is the mean influent concentration, and C_{out} is the mean effluent concentration of the parameter of interest. For EC and pH, influent-to-effluent comparisons were reported descriptively due to the fundamentally different nature of salinity and acidity control versus pollutant removal [18].

2.4.3. Seasonal Performance Analysis

Monthly effluent quality data were aggregated into four meteorological seasons to identify temporal patterns in treatment performance: Winter (December–February), Spring (March–May), Summer (June–August), and Autumn (September–November). Seasonal mean concentrations were calculated for each parameter and compared across seasons to assess the magnitude of temperature-driven and hydraulic loading-driven performance variations [20–22].

2.5. Probabilistic Risk Assessment via Monte Carlo Simulation

A Monte Carlo simulation (MCS) framework was implemented to quantify compliance probabilities and exceedance risks under observed effluent quality variability. This probabilistic approach explicitly accounts for the inherent uncertainty and temporal variability in treatment performance, providing a more complete risk characterization than deterministic single-point compliance assessments [23, 25, 26].

2.5.1. Probability Distribution Fitting

Based on the central limit theorem and empirical evidence from analogous WWTP monitoring datasets,

each effluent quality parameter was modeled as a normally distributed random variable:

$$X \sim N(\mu, \sigma^2) \quad (5)$$

where X represents the simulated effluent concentration, μ is the population mean estimated by the sample mean, and σ^2 is the population variance estimated by the sample variance. Distribution parameters were derived directly from the descriptive statistics computed in Section 2.4.1 [22, 27].

2.5.2. Simulation Protocol

For each effluent quality parameter, $N = 100,000$ pseudo-random values were generated from the fitted normal distribution using a Mersenne Twister pseudo-random number generator algorithm, which provides excellent statistical properties for large-scale Monte Carlo applications [25, 26]. The iteration counts of 100,000 was selected to ensure probability estimates stable to three decimal places, yielding a Monte Carlo standard error of approximately $\pm 0.16\%$ for probability estimates near 50%.

2.5.3. Compliance Probability and Non-Compliance Risk

For each parameter and each reuse category, the parameter-specific compliance probability was calculated as:

$$P_{Compliant} = \left(N_{Compliant} / N_{Total} \right) \times 100 \quad (6)$$

where $N_{compliant}$ is the number of simulated realizations satisfying the applicable standard limit, and $N_{total} = 100,000$ is the total number of simulation iterations. The parameter-specific exceedance risk was defined as:

$$Risk (\%) = (N_{exceed} / N_{Total}) \times 100 = 100 - P_{Compliance} \quad (7)$$

where N_{exceed} is the number of simulated values exceeding the regulatory threshold [23, 27].

2.5.4. Overall Multi-Parameter Compliance Probability

For multi-parameter compliance assessment, the overall compliance probability was calculated as:

$$P_{Overall} = \left(N_{All Compliant} / N_{Total} \right) \times 100 \quad (8)$$

where $N_{all compliant}$ is the number of simulation iterations in which all five parameters simultaneously satisfied their respective thresholds. This joint compliance probability is more conservative and operationally meaningful than individual parameter compliance probabilities, since failure to meet any single parameter limit renders the effluent unsuitable for the intended reuse application [23, 25, 26]. The entire Monte Carlo simulation framework was implemented in MATLAB

R2024b (MathWorks, Natick, MA, USA) using the built-in `normrnd` function for pseudorandom variate generation and vectorized logical operations for compliance evaluation.

3. Results and Discussion

The performance of the Ramshar WWTP was evaluated using a combination of descriptive statistical analysis, temporal trend assessment, regulatory compliance evaluation, and probabilistic risk modeling. This comprehensive approach provides a thorough understanding of the stability and reliability of the plant's effluent quality under both observed and simulated conditions. The results are presented with supporting numerical summaries in Tables 2–4 and graphical visualizations in Figures 1–5.

3.1. Descriptive Statistics of Effluent Quality

The descriptive statistics for the key effluent quality parameters are presented in Table 2. These statistics provide initial insight into the central tendency and variability of effluent concentrations during the 12-month monitoring period.

Table 2. Descriptive statistics of treated effluent quality parameters at the Ramshar WWTP during the monitoring period.

Parameter	Mean	Standard Deviation	Minimum	Maximum
BOD ₅ (mg/L)	34.83	6.03	25	45
COD (mg/L)	55.83	7.43	45	70
TSS (mg/L)	16.83	3.69	12	24
EC (μS/cm)	500.00	24.86	460	540
pH	7.82	0.09	7.70	7.90

BOD₅ exhibited a mean concentration of 34.83 mg/L with a standard deviation of 6.03 mg/L, indicating generally stable organic loading in the treated effluent. COD concentrations averaged 55.83 ± 7.43 mg/L, demonstrating effective removal of oxidizable organic compounds. TSS levels were low and consistent, with a mean of 16.83 mg/L and standard deviation of only 3.69 mg/L, suggesting efficient clarification and solids separation. The mean EC of 500 μS/cm (± 24.86 μS/cm) indicated low salinity levels, while pH remained nearly constant at 7.82 ± 0.09 , reflecting stable chemical conditions throughout the treatment process.

These results indicate strong operational stability throughout the study period. The probability density functions (PDFs) of the monitored parameters, presented in Figure 1, and cumulative distribution functions (CDFs), shown in Figure 2, reveal that the parameters closely follow approximately normal distributions with minimal skewness, particularly for EC and pH. BOD₅ and COD exhibited slightly wider spread, consistent with their biological sensitivity to operational and environmental fluctuations.

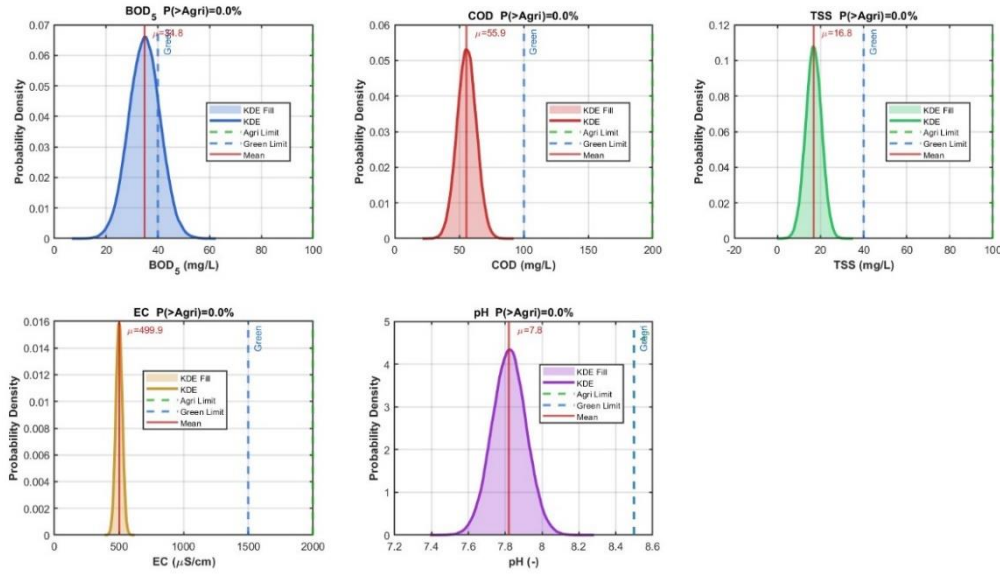


Figure 1. Probability density functions (PDFs) of the main effluent quality parameters (BOD₅, COD, TSS, EC, and pH) based on the observed dataset.

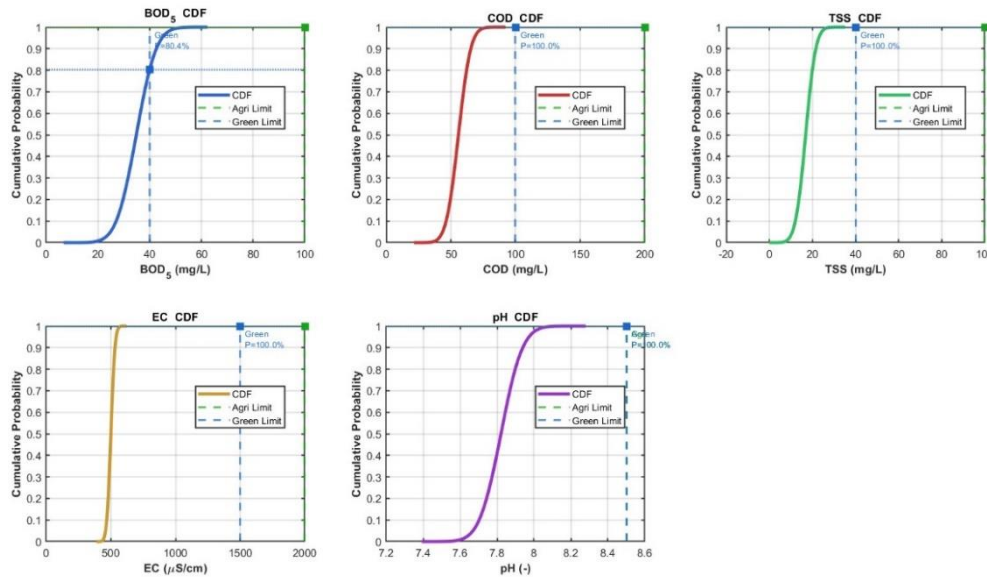


Figure 2. Cumulative distribution functions (CDFs) of effluent quality parameters illustrating the probability of exceeding irrigation standards.

3.2. Temporal Variation and Seasonal Trends

Monthly variations of effluent quality parameters are illustrated in Figure 3, providing a detailed assessment of temporal behavior throughout the monitoring year. Seasonal and operational factors exert significant influence on biological treatment processes; therefore, understanding temporal patterns is essential for evaluating system robustness and identifying periods of potential vulnerability.

BOD₅ and COD Seasonal Trends. BOD₅ and COD demonstrated mild seasonal fluctuations, with slightly elevated concentrations during colder months. This

trend was anticipated, as lower temperatures reduce microbial metabolic activity, thereby decreasing the biodegradation rate of organic matter. During winter, BOD₅ values approached the upper limit of the green space irrigation standard (40 mg/L), although they remained safely below the agricultural irrigation limit (100 mg/L). COD followed a similar seasonal pattern but maintained concentrations comfortably within both regulatory thresholds throughout the year. The variability observed in BOD₅ and COD is further supported by their wider interquartile ranges in the box-and-whisker plots presented in Figure 4, indicating sensitivity to seasonal shifts and operational dynamics.

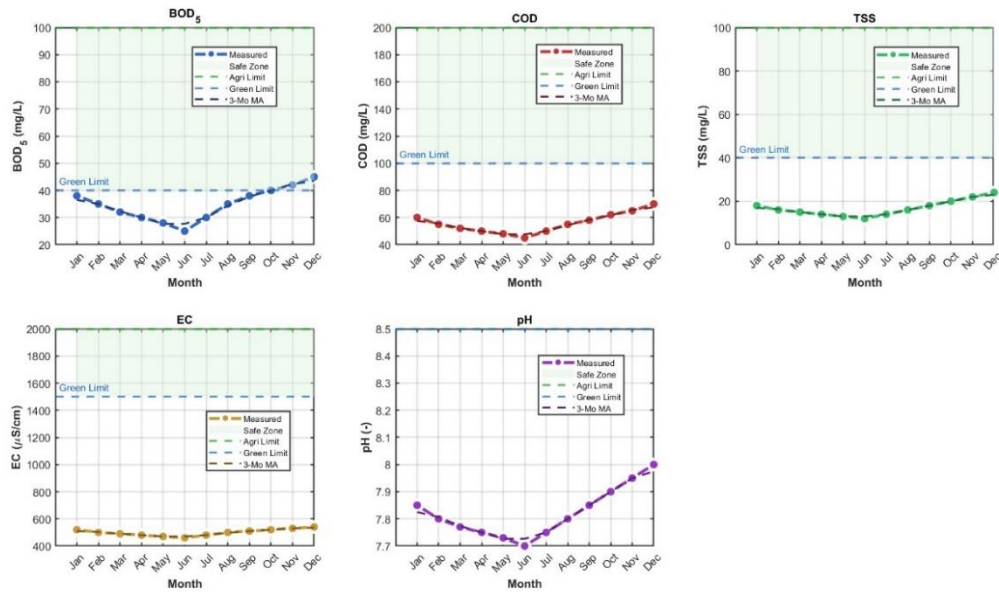


Figure 3. Monthly variation of effluent quality parameters at the Ramshar wastewater treatment plant during the monitoring period.

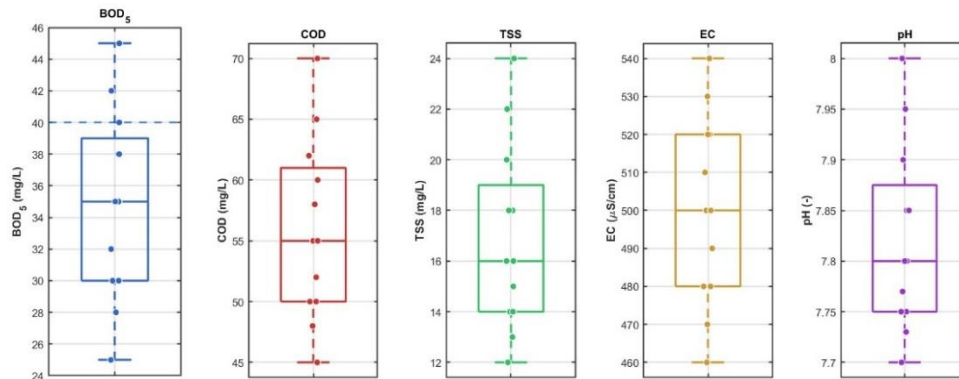


Figure 4. Box-and-whisker plots showing the distribution and variability of effluent quality parameters.

TSS, EC, and pH Stability. TSS exhibited minimal seasonal variability, underscoring consistent sedimentation and sludge management efficiency. The narrow interquartile range in Figure 4 and the minimal month-to-month variation in Figure 3 confirm that solids removal was highly stable throughout the year. EC remained nearly constant at approximately 500 $\mu\text{S}/\text{cm}$, with only minimal fluctuations, indicating stable influent salinity and effective hydraulic operation. Similarly, pH varied only slightly, remaining consistently between 7.7 and 7.9—a range ideal for biological processes and irrigation reuse.

3.3. Compliance Assessment with Irrigation Reuse Standards

Compliance with national standards for agricultural and green space irrigation was evaluated using the observed dataset. The results are summarized in Table 3.

Table 3. Compliance assessment of treated effluent with agricultural and green space irrigation standards.

Parameter	Mean Value	Agricultural Standard	Compliance (%)	Green Space Standard	Compliance (%)
BOD ₅ (mg/L)	34.83	≤ 100	100	≤ 40	96.7
COD (mg/L)	55.83	≤ 200	100	≤ 100	100
TSS (mg/L)	16.83	≤ 100	100	≤ 40	100
EC ($\mu\text{S}/\text{cm}$)	500	≤ 2000	100	≤ 1500	100
pH	7.82	6.5–8.5	100	6.5–8.5	100

Agricultural Irrigation Standards. All monitored parameters satisfied agricultural irrigation standards throughout the entire monitoring period, yielding 100% compliance. BOD₅ remained substantially below the agricultural limit of 100 mg/L, COD was significantly lower than its threshold of 200 mg/L, TSS never exceeded its 100 mg/L limit, EC was well below the salinity guideline of 2,000 $\mu\text{S}/\text{cm}$, and pH remained within the acceptable range of 6.5–8.5. This complete compliance confirms that the effluent is consistently suitable for agricultural irrigation, with a robust safety

margin that enhances reliability under varied environmental conditions.

Green Space Irrigation Standards. Green space irrigation standards impose more stringent thresholds, particularly for BOD₅, which must remain below 40 mg/L. The observed data indicated a compliance rate of 96.7%, with only occasional marginal exceedances of BOD₅ during colder months. COD, TSS, EC, and pH all maintained 100% compliance with their respective thresholds. These results indicate that the plant's effluent is generally well-suited for landscape irrigation, although minor operational refinements could further enhance reliability under the more stringent standard.

3.4. Probabilistic Exceedance Analysis Using Monte Carlo Simulation

While compliance analysis based solely on observed data provides important evidence of performance, it does not account for uncertainty or variability beyond the monitoring period. Accordingly, a Monte Carlo simulation with 100,000 iterations was conducted using the descriptive statistical parameters as probabilistic inputs. The results are presented in Table 4.

Table 4. Monte Carlo simulation results (100,000 iterations) showing exceedance probabilities relative to irrigation quality standards.

Parameter	Simulated Mean	Agricultural Limit	Exceedance (%)	Green Space Limit	Exceedance (%)
BOD ₅ (mg/L)	34.83	100	0.00	40	19.41
COD (mg/L)	55.83	200	0.00	100	0.00
TSS (mg/L)	16.83	100	0.00	40	0.00
EC (μS/cm)	500	2000	0.00	1500	0.00
pH	7.82	6.5–8.5	0.00	6.5–8.5	0.00

Agricultural Irrigation Risk. The simulation indicated zero probability of exceeding agricultural thresholds for all parameters, reflecting the substantial operational buffer between observed concentrations and regulatory limits. Low variability in TSS, EC, and pH, combined with moderate but safe variability in BOD₅ and COD, collectively contribute to this zero-risk outcome, reinforcing the reliability of the WWTP for agricultural reuse applications.

Green Space Irrigation Risk. The Monte Carlo results revealed a more nuanced risk profile for green space irrigation. COD, TSS, EC, and pH exhibited 0% exceedance probability, while BOD₅ displayed a 19.41% probability of exceeding the 40 mg/L threshold. This exceedance probability aligns with the PDF and CDF behavior presented in Figures 1 and 2, where the distribution tail intersects the regulatory threshold. It is important to emphasize that although the 19.41% exceedance probability may appear substantial, it applies exclusively to the more stringent green space threshold; BOD₅ concentrations never approach the agricultural limit in either observed or simulated data.

3.5. Integrated Interpretation of Plant Performance

Taken together, the descriptive and probabilistic results paint a consistent picture of a treatment facility

that operates with notable stability. The remarkably narrow ranges observed for EC and pH point to a steady influent composition and well-controlled chemical environment throughout the year, while the consistently low TSS values attest to effective solid–liquid separation at the clarification stage. COD and BOD₅ do show somewhat greater variability—an expected outcome given their dependence on biological processes—yet they remain comfortably within safe operating ranges. The radar chart in Figure 5, which maps normalized mean effluent values against both sets of regulatory thresholds, visually reinforces this point: a pronounced buffer zone separates the measured concentrations of EC, pH, TSS, and COD from their respective limits, while BOD₅ sits noticeably closer to its green space threshold—the one parameter where continued vigilance is warranted.

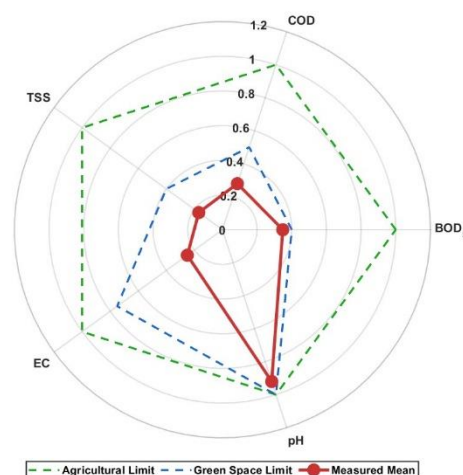


Figure 5. Radar chart comparing normalized mean effluent concentrations with agricultural and green space irrigation standards.

From a broader perspective, these results position the Ramshar WWTP as a reliable producer of reclaimed water suitable for agricultural reuse and, for the most part, acceptable for green space irrigation as well. It is worth noting that both COD (55.83 mg/L) and TSS (16.83 mg/L) fell well below their national thresholds throughout the monitoring campaign, a finding that speaks to effective organic removal and efficient sedimentation regardless of the time of year. Perhaps most noteworthy is the low effluent EC of 500 μS/cm—a value that is by no means guaranteed in an arid setting where saline influent often constrains reuse potential. The fact that Ramshar maintained such low salinity levels suggests a favorable influent profile and sound hydraulic management, distinguishing it from many comparable facilities in semi-arid climates where elevated EC remains a persistent bottleneck for irrigation reuse.

Where the data do reveal a point of concern is in the behavior of BOD₅. On average, the measured BOD₅

concentration (34.83 mg/L) did satisfy both the agricultural and green space thresholds; however, the Monte Carlo simulation tells a more cautionary story, revealing a 19.41% likelihood that the 40 mg/L landscape irrigation ceiling could be breached under realistic operating variability. This finding is not altogether surprising. BOD₅ removal is governed by living microorganisms whose metabolic rates respond to ambient temperature, hydraulic loading patterns, and the ever-shifting composition of the incoming wastewater. When temperatures drop in winter, microbial activity slows, oxygen transfer becomes less efficient, and treatment performance inevitably softens. Comparable seasonal swings have been documented in activated sludge plants operating under similar climatic gradients elsewhere, lending support to the view that this variability is an inherent feature of biological treatment rather than a sign of operational failure.

That said, it is equally important to keep this finding in perspective. Even under the full range of simulated conditions, the plant never came close to violating the more lenient agricultural irrigation thresholds. The distinction matters: agricultural soils possess a natural capacity to buffer organic loads through microbial decomposition, whereas public green spaces—parks, recreational areas, ornamental landscapes—demand tighter control to avoid odor issues and maintain aesthetic standards. Because the Ramshar facility currently operates near the upper boundary of the green space BOD₅ limit, relatively modest interventions could yield meaningful improvements. Practical options worth exploring include boosting aeration intensity during the cooler months when microbial kinetics are most sluggish, fine-tuning the sludge retention time to maintain a more active biomass, or introducing a low-cost tertiary polishing step—for example, a sand filter or a small constructed wetland—to shave the final few milligrams off the effluent BOD before discharge.

3.6. Significance of the Analytical Framework

A broader methodological lesson emerges from this work. Conventional compliance assessments that rely on comparing monthly averages against fixed thresholds can obscure the true risk profile of a treatment system. A mean value that sits comfortably below a limit may mask occasional tail events that are operationally significant but invisible to deterministic analysis. By contrast, the Monte Carlo approach adopted here captures the full spread of plausible outcomes, revealing precisely where and how often the system may fall short. In the present case, the simulation confirmed what the observed data hinted at—that four of the five monitored parameters carry virtually no compliance risk—while simultaneously quantifying the one parameter, BOD₅ as the critical control parameter for green space reuse. This kind of targeted diagnostic is exactly what plant operators and water managers need: rather than prescribing blanket upgrades across the entire treatment

train, the probabilistic results direct attention—and limited budgets—to the single process stage most likely to benefit from improvement. For water-stressed regions such as Iran's Sistan and Baluchestan Province, where every cubic meter of reclaimed water carries strategic value, such evidence-based precision in reuse planning can make the difference between a facility that merely treats wastewater and one that actively strengthens regional water security.

4. Conclusions

This study set out to answer a straightforward but consequential question: can the Ramshar Wastewater Treatment Plant be relied upon to supply reclaimed water of sufficient quality for agricultural and landscape irrigation? To address this question, a year-long monitoring campaign was combined with an analytical framework that moved beyond simple threshold comparisons to include descriptive statistics, seasonal trend analysis, and a 100,000-iteration Monte Carlo simulation. The evidence points to a clear answer.

Across all twelve months of monitoring, the mean effluent concentrations of the five target parameters—BOD₅ (34.83 mg/L), COD (55.83 mg/L), TSS (16.83 mg/L), EC (500 μ S/cm), and pH (7.82)—remained well within the permissible limits set by Iranian Standard No. 2901 for both agricultural and green space reuse categories. The tight clustering of individual measurements around these means, reflected in consistently small standard deviations, speaks to a treatment process that operates with a reassuring degree of predictability.

Compliance assessment revealed that not a single monthly sample violated the agricultural irrigation thresholds—a perfect record that underscores the plant's reliability as a reclaimed water source for crop irrigation. Under the tighter green space criteria, overall compliance still exceeded 96%, with only BOD₅ occasionally brushing against the 40 mg/L limit during colder months when biological activity naturally slows.

The Monte Carlo simulation added an important layer of insight that deterministic analysis alone could not provide. By generating 100,000 plausible effluent scenarios, the simulation confirmed that the risk of exceeding agricultural standards is, for all practical purposes, zero. For landscape irrigation, the picture is more nuanced: BOD₅ carries a 19.41% chance of exceeding the 40 mg/L green space limit, while every other parameter shows no exceedance risk whatsoever. This probabilistic lens transforms a seemingly marginal compliance issue into a quantified and therefore manageable risk.

Seasonal trends, while detectable in the organic parameters, proved to be modest in magnitude and did not fundamentally compromise effluent quality at any point during the year. The winter dip in biological treatment performance is a well-documented phenomenon and, in this case, remained within bounds

that do not warrant alarm—though they do warrant attention.

Taken as a whole, the evidence leaves little doubt that the Ramshar WWTP is a well-functioning facility capable of delivering reclaimed water that meets agricultural irrigation requirements with a wide margin of safety, and that largely satisfies the stricter demands of green space irrigation as well. The integrated analytical framework presented here—blending statistical characterization with probabilistic risk quantification—offers a transferable template that other facilities in water-scarce regions can adopt to move beyond pass/fail compliance checking toward genuinely risk-informed reuse planning. Looking ahead, targeted improvements in BOD₅ control—whether through seasonally adjusted aeration, more deliberate sludge age management, or the addition of a simple polishing stage such as a sand filter or constructed wetland—represent realistic, cost-effective measures that could close the remaining gap with the most stringent reuse criteria. In a region where every drop of recoverable water counts, such incremental gains carry outsized strategic value for long-term water security.

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