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Comprehensive Assessment of Biological Nutrient Removal Performance in Carrousel-Type Activated Sludge Systems adopted by wastewater treatment plant in Jazan, KSA

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Abstract
This study presents a comprehensive process design analysis of the Jazan Sewage Treatment Plant (STP) on the Red Sea coast of Saudi Arabia, employing a Carrousel-type oxidation ditch with Oxidation–Reduction Potential (ORP)-controlled intermittent aeration for biological nutrient removal. The analysis covers all unit operations from preliminary treatment through effluent disinfection across two design phases (20,004 and 37,003 m^3/day for Phase 1 and the combined Phase 1 + Phase 2 capacity, respectively, derived from projected population equivalents of 100,000 and 185,000 inhabitants at a per-capita generation rate of 200 L/capita/day), and validates the design calculations against 29 months of effluent monitoring data (January 2023 – July 2025, representing all monitoring records available at the time of analysis). The extended aeration configuration (Solids Retention Time, SRT = 16.9 days, Hydraulic Retention Time, HRT = 30.05 hours) provides a denitrification safety factor of 1.53. Operational monitoring confirms that actual performance substantially exceeds design targets, achieving removal efficiencies of 98.5% for five-day biochemical oxygen demand (BOD5) (mean effluent 4.19 mg/L vs. ≤25 design), 99.0% for total suspended solids (TSS) (2.77 mg/L), 91.4% for total nitrogen (TN) (5.19 mg/L vs. 83.3% design), and 88.7% for total phosphorus (TP) (2.04 mg/L vs. 55.6% design). The marked phosphorus removal suggests effective enhanced biological phosphorus removal under ORP-controlled intermittent aeration. Comparative analysis with Carrousel installations at Wangtang, China (HRT = 5.3 h) and Al-Qateef, Saudi Arabia (HRT = 14.9 h) confirms that the Jazan design adopts a deliberately conservative approach with significantly longer hydraulic retention time, prioritizing operational stability under arid coastal climatic conditions. This study provides a documented and operationally validated design methodology applicable to similar arid coastal municipalities.

Keywords: ORP-controlled aeration; Oxidation ditch; Wastewater treatment; Extended aeration; Denitrification

Abbreviations: ASM – Activated Sludge Model; BOD5 – Five-day Biochemical Oxygen Demand; COD – Chemical Oxygen Demand; DO – Dissolved Oxygen; DWF – Dry Weather Flow; EBPR – Enhanced Biological Phosphorus Removal; F/M – Food-to-Microorganism ratio; HRT – Hydraulic Retention Time; MCRT – Mean Cell Residence Time; MLSS – Mixed Liquor Suspended Solids; MWE – Ministry of Water and Electricity (Saudi Arabia); NH3-N – Ammonia Nitrogen; NO3-N – Nitrate Nitrogen; NO2-N – Nitrite Nitrogen; ORP – Oxidation–Reduction Potential; PAO – Phosphorus-Accumulating Organism; PO4-P – Orthophosphate; SND – Simultaneous Nitrification–Denitrification; SRT – Solids Retention Time; SS – Suspended Solids; STP – Sewage Treatment Plant; TDS – Total Dissolved Solids; TN – Total Nitrogen; TP – Total Phosphorus; TSS – Total Suspended Solids; WWTP – Wastewater Treatment Plant.

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1. Introduction

The city of Jazan is the capital of the Jazan Region in southwestern Saudi Arabia, situated along the Red Sea coast at approximately 16.9°N latitude. The region experiences an arid tropical climate with high ambient temperatures, which significantly influences wastewater characteristics and treatment process kinetics. As urbanization has accelerated across Saudi Arabian cities, the need for advanced wastewater treatment facilities that can meet stringent effluent standards while operating efficiently under local climatic conditions has become increasingly critical (Drewes et al., 2012; Haider et al., 2021).

Saudi Arabia faces significant water scarcity challenges exacerbated by its arid climate and limited freshwater resources. Wastewater treatment and reuse have emerged as critical strategies for sustainable water management in the Kingdom (Aleisa & Al-Zubari, 2017; Dawoud, 2011). Currently, approximately 70 sewage treatment plants operate throughout the country, with conventional activated sludge systems being the most common secondary treatment technology (Alhajri et al., 2025). The Ministry of Water and Electricity has established design guidelines specifically tailored for wastewater treatment plants operating under Saudi Arabian conditions (MWE, 2006). Within this national framework, the Jazan Region presents unique challenges due to its coastal location along the Red Sea, high ambient temperatures exceeding 35°C for much of the year, and the ecological sensitivity of the receiving marine environment.

The Jazan Sewage Treatment Plant was designed in 1999. The plant employs a Carrousel-type oxidation ditch system, which represents a modified form of the extended aeration activated sludge process. The Carrousel system was originally developed in the Netherlands in the 1970s and has gained worldwide recognition for its ability to achieve simultaneous nitrification-denitrification through the creation of alternating aerobic and anoxic zones within the same reactor volume (Xu et al., 2017).

Oxidation ditch technology has been widely adopted globally for municipal wastewater treatment, particularly in small-to-medium scale facilities, due to its advantages of simple construction, flexible operation, low sludge production, and inherent capability for simultaneous nitrification and denitrification (Zhou et al., 2015; Ammary & Radaideh, 2005). Liu et al. (2010) demonstrated that simultaneous nitrification and denitrification (SND) in Carrousel oxidation ditches can achieve 60-70 total nitrogen removal efficiency with hydraulic retention times of 4-6 hours. Then, Xie et al. (2011) showed that integration of the Activated Sludge Model 2d (ASM2d) with optimization algorithms can further enhance Carrousel system performance. Yang et al. (2011) utilized computational fluid dynamics (CFD) to optimize energy consumption and effluent quality in full-scale oxidation ditch systems.

The integration of ORP (Oxidation-Reduction Potential)-controlled intermittent aeration into the Carrousel design represents a significant advancement over conventional continuous aeration systems. Li and Bishop (2002) demonstrated through year-long field testing at three full-scale wastewater treatment plants that ORP values correlate well with nutrient removal efficiency, with nitrification occurring at ORP values above 380 mV and organic substrate oxidation at approximately 250 mV. Charpentier et al. (1989) established that ORP-based aeration control can optimize energy consumption while improving both carbonaceous and nitrogenous pollutant removal. Chang and Hao (1996) showed that ORP-controlled intermittent aeration in extended aeration systems can achieve total nitrogen removal exceeding 93% with residual effluent TN of only 2.94 mg/L. Lu et al. (2000) further confirmed that for simultaneous carbon and nitrogen removal, optimal ORP set-points should range between −50 mV and +175 mV.

Recent investigations have continued to refine the understanding of Carrousel and oxidation ditch performance. Alhajri et al. (2025) provided an updated national review of wastewater treatment in Saudi Arabia and projected the 2035 reuse demand, concluding that conventional activated sludge variants-including oxidation ditches-will remain the dominant secondary treatment route, yet identifying nutrient removal under hot-arid conditions as the principal performance bottleneck. In a comparable Saudi context, Alramthi et al. (2022) analyzed seven years of influent, effluent and operational data from the Bishah Governorate oxidation ditch in Saudi Arabia and demonstrated consistent compliance with national and international reuse standards, illustrating both the long-term durability of the technology under arid conditions and the diagnostic value of multi-year operational records. Liu et al. (2025) compared Carrousel oxidation ditches against high-efficiency multi-cycle A2/O processes for urban wastewater treatment and reported that the oxidation ditch configuration retains a robust performance envelope, particularly where stable effluent quality is prioritized over compactness. With specific reference to aeration control, the recent review by Owaes et al. (2024) on operational strategies for partial and conventional nitrification documented that real-time control schemes coupling redox potential and pH outperform dissolved-oxygen-only strategies for nitrification-denitrification, while highlighting the relative scarcity of long-term full-scale validation datasets. In parallel, Navada and Vadstein (2022) synthesized the evidence that brackish-water salinities of approximately 9-12‰ constitute a critical inhibition threshold for nitrifier communities, with substantial drops in nitrification capacity above 8-15‰, implying that direct transfer of temperate-climate criteria to Saudi coastal plants-where groundwater infiltration may drive influent salinity into this range-is not advisable. Critical re-examination of these contributions reveals three persistent gaps: (i) the absence of operationally validated, end-to-end process design audits for Carrousel systems located on hot-arid coastlines; (ii) limited reporting of paired design-versus-actual performance datasets covering sustained operational periods; and (iii) insufficient discussion of how conservative hydraulic retention times interact with EBPR and SND under simultaneously high temperature, elevated salinity and ORP-controlled aeration. The present study directly addresses these three gaps by combining a full design verification of the Jazan STP against established criteria with a 29-month operational performance validation under representative arid-coastal conditions.

Despite the growing number of wastewater treatment facilities in Saudi Arabia, detailed process design documentation for plants operating under arid coastal conditions remains limited in the published literature. This paper addresses that gap by presenting a comprehensive analysis of the complete process design calculations for the Jazan Sewage Treatment Plant, covering all major unit operations from preliminary treatment through effluent disinfection and sludge handling. Beyond documenting the design methodology, the analysis evaluates the adequacy of the adopted design parameters against established engineering criteria and published data from comparable Carrousel oxidation ditch installations in China and Saudi Arabia. This comparative framework serves not merely as a benchmarking exercise, but rather as a diagnostic tool to identify design margins, potential operational limitations, and optimization opportunities specific to high-temperature, high-salinity influent conditions characteristic of arid coastal environments. By systematically linking design inputs to treatment performance outcomes, this study aims to provide a replicable technical reference that supports evidence-based decision-making for the design and upgrading of similar facilities in climatically analogous regions.

2. Methodology

The analytical approach adopted in this study is based on a systematic review of the original process design documentation prepared for the Jazan STP. Design calculations for each unit operation were independently verified against established engineering criteria, primarily from Metcalf & Eddy (1991), WEF/ASCE (1998), and the Saudi MWE (2006) design guidelines. Each design parameter was evaluated by comparing the adopted value against the recommended criteria range for the corresponding treatment technology. The nitrogen and phosphorus removal capacities were recalculated using the Kayser (1991) denitrification correlation and mass balance principles. A comparative benchmarking analysis was conducted against published operational data from two Carrousel oxidation ditch installations: the Wangtang WWTP in China (Xie et al., 2011) and the Al-Qateef WWTP in Saudi Arabia (Elsergany, 2014). Additionally, effluent monitoring data collected over a 29-month dataset (2023-2025), covering 16 physicochemical parameters were compiled from the plant laboratory records to validate the design calculations against actual operational performance (Section 11).

3. Site Description and Design Basis

3.1 Overview

The Jazan Sewage Treatment Plant (STP) is a municipal wastewater facility located in Jazan city on the Red Sea coast of southwestern Saudi Arabia (Fig. 1). The plant employs a Carrousel oxidation ditch system with ORP-controlled intermittent aeration for biological nutrient removal, and operates in two phases with design capacities of 20,004 m³/day (Phase 1) and 37,003 m³/day (Phase 2), corresponding to design population equivalents of approximately 100,000 and 185,000 inhabitants, respectively, based on an estimated per capita wastewater generation rate of 200 L/capita/day. The plant serves the sewered population of Jazan city, which had a total population of approximately 200,000 according to the 2022 Saudi Census (GAS, 2022); however, not all residents are connected to the centralized sewer network, with some areas still relying on septic tank systems.

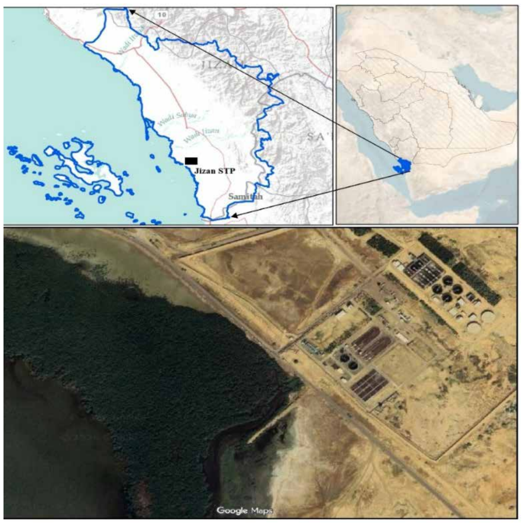

Figure 1: Site location map and satellite image of the Jazan Sewage Treatment Plant, Jazan Region, Saudi Arabia.

3.2 Design Loadings

The plant was designed in two phases to accommodate projected population growth. The hydraulic design of the Jazan STP was structured in two developmental phases to accommodate projected population growth and increasing wastewater generation. Under Phase 1, the plant was designed to treat an average daily flow of 20,004 m³/day, with a peak hourly capacity of 1,667.0 m³/hr, applying a peak factor of 2:1. The full-scale configuration (Phase 1 + Phase 2) was designed to nearly double the treatment capacity, accommodating an average daily flow of 37,003 m³/day, a peak hourly flow of 3,083.6 m³/hr, and a corresponding peak flow rate of 860 L/sec. The design flows of 20,004 and 37,003 m³/day are not arbitrary round numbers; they are derived from population-equivalent calculations carried out for Jazan city by the original design consultant (Phase 1 horizon: 100,020 inhabitants × 200 L/capita/day = 20,004 m³/day; ultimate horizon: 185,015 inhabitants × 200 L/capita/day = 37,003 m³/day). The slightly "non-round" values therefore preserve the traceability of the design to its underlying demographic assumptions and have been retained throughout this paper rather than rounded for presentation purposes.

3.3 Influent Wastewater Characteristics

The influent wastewater characteristics were based on average loads typical to Saudi Arabia. The influent BOD_5 concentration of 275 mg/L falls within the reported range of 150-450 mg/L for Saudi Arabian domestic wastewater, consistent with the medium-strength classification in Metcalf & Eddy (1991, Table 3-16). The COD:BOD ratio of 2:1 confirms the predominantly domestic nature of the wastewater. Fig. 2 presents a comparative visualization of the influent concentrations and mass loadings for Phase 1 and the combined Phase 1 + Phase 2 capacity, highlighting the proportional increase in organic and nutrient loads associated with the plant expansion.

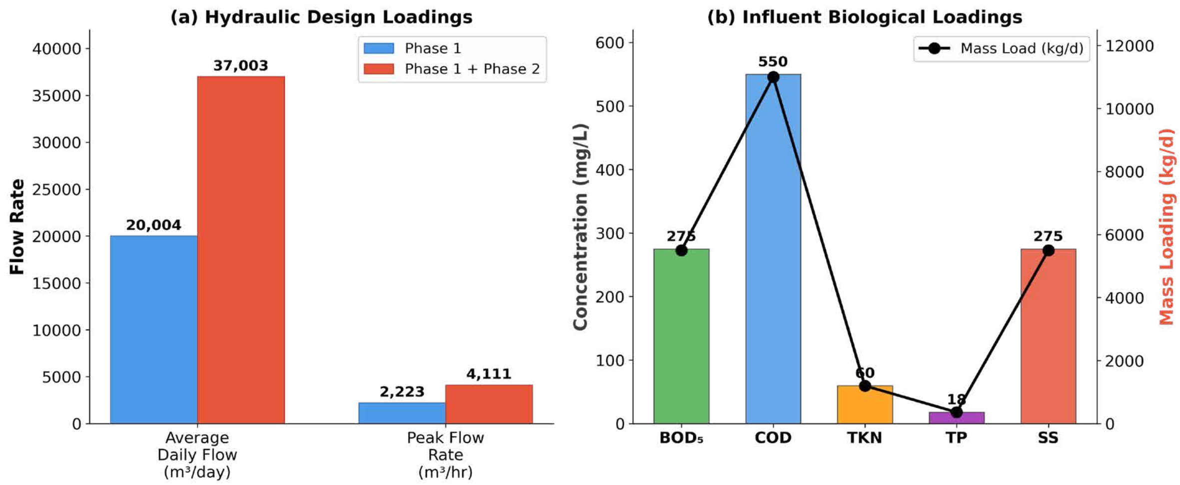

Figure 2: Design Loadings - Hydraulic and Biological Parameters

3.4 Effluent Quality Standards

The guaranteed final effluent standards are presented in Table 1. These targets are consistent with the general secondary treatment standards applicable at the time of design (1999). While BOD_5 and SS are subject to contractual guaranteed limits of ≤ 25 mg/L, corresponding to a minimum removal efficiency of 90.9%, no contractual guarantees were specified for nutrient removal. Nevertheless, the Carrousel oxidation ditch system, operating with ORP-controlled intermittent aeration, is anticipated to achieve total nitrogen and total phosphorus concentrations of ≤ 10 mg/L and ≤ 8 mg/L, respectively, through biological nitrification-denitrification and enhanced biological phosphorus removal (EBPR) mechanisms. It is worth noting that the 1999 design predates the more stringent Saudi MWE (2006) discharge standards for unrestricted reuse applications (Al-Jasser, 2011), which mandate $BOD_5 \leq 10$ mg/L, SS ≤ 10 mg/L, TN ≤ 10 mg/L, and TP ≤ 1 mg/L for unrestricted reuse applications. Consequently, while the plant's organic removal targets remain broadly adequate, the anticipated phosphorus removal of 55.6% falls considerably short of current regulatory requirements, suggesting that supplementary chemical phosphorus removal or process optimization may be required to meet present-day compliance thresholds.

Table 1: Final Effluent Quality Standards and Anticipated Performance

Parameter	Guaranteed	Anticipated	Removal %
BOD_5 (mg/L)	≤ 25	≤ 25	90.9%
SS (mg/L)	≤ 25	≤ 25	90.9%
Total N (mg/L)	-	≤ 10	83.3%
Total P (mg/L)	-	≤ 8	55.6%

4. Process Description

The Jazan STP process train consists of the following major unit operations: (1) inlet works screening, (2) grit removal, (3) Carrousel aeration system, (4) secondary settlement tanks, (5) sludge recycle and wasting, (6) sludge thickening, (7) sludge drying beds, and (8) chlorine contact disinfection. The overall process flow diagram is presented in Fig. 3.

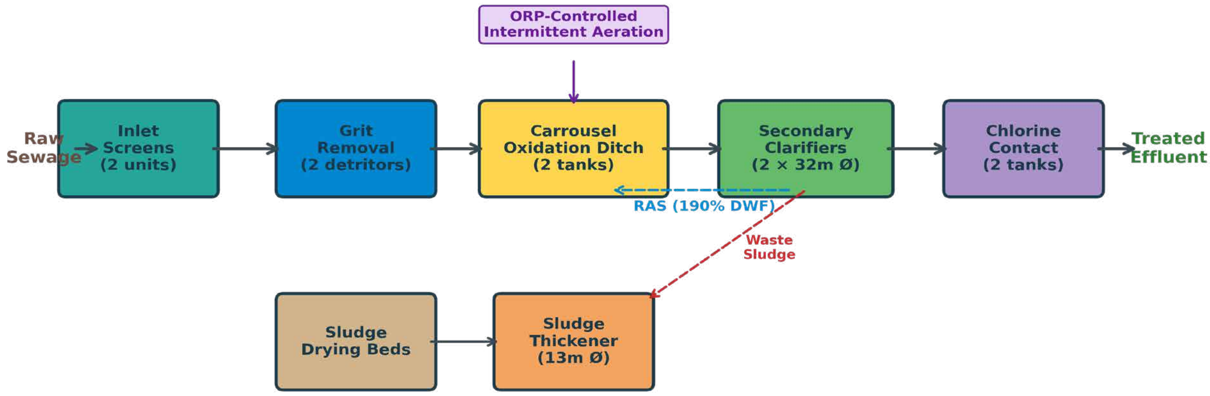

Figure 3: Jazan STP Process Flow Diagram - Carrousel Oxidation Ditch System

5. Preliminary Treatment

5.1 Inlet Works Screens

The inlet works screening equipment is designed for Phase 2 flows (37,003 m³/day average, 860 L/sec peak). The design parameters conform to the criteria established in Metcalf & Eddy (1991, Table 9-2) for mechanically cleaned bar racks. Screen channel width of 1.25 m provides maximum velocity of 0.82 m/sec at peak flow, within the design criterion of 0.9 m/sec. Table 2 summarizes the design verification.

Table 2: Inlet Works Screen Design Parameters

Parameter	Design Value	Criteria Range
Number of screens	2	-
Peak flow rate per screen (L/sec)	430	-
Channel width (m)	1.25	-
Clear opening between bars (mm)	19	15-75
Min. velocity at avg flow (m/s)	0.600	0.6-0.9
Max. velocity at peak flow (m/s)	0.82	≤ 0.9

5.2 Grit Removal

Two detritor-type grit removal units achieve 95% removal efficiency for particles down to 0.21 mm (65-mesh), consistent with design guidelines in Metcalf & Eddy (1991, Table 9-3). The average detention time of 42 seconds is slightly below the lower bound of the typical design range of 45-90 seconds, while the horizontal velocity of 0.27 m/sec falls within the recommended range of 0.25-0.40 m/sec (Table 3). The marginally shorter detention time is considered acceptable given the conservative horizontal velocity and adequate removal efficiency.

Table 3: Grit Removal Design Parameters

Parameter	Design Value	Criteria
Number of detritors	2	-
Removal efficiency	95% (≥ 0.21mm)	65-mesh
Surface area per detritor (m²)	36	-
Average detention time (sec)	42.0	45-90
Horizontal velocity (m/sec)	0.27	0.25-0.40

6. Biological Treatment - Carrousel Aeration System

6.1 Design Concept

The heart of the Jazan STP is a Carrousel-type oxidation ditch equipped with vertical shaft aerators. Nitrogen removal occurs through alternating oxygen-rich and oxygen-poor zones within the channels. In zones where dissolved oxygen exceeds 0.5 mg/L, ammonium is oxidized to nitrate (nitrification), while in low-oxygen zones, nitrate is reduced to nitrogen gas (denitrification). This mechanism is consistent with the SND observations reported by Liu et al. (2010) and Zhou et al. (2015) in full-scale Carrousel systems.

The proposed design incorporates ORP-controlled intermittent aeration. The redox potential indicates the ratio of oxidizable to reducible materials in the water. High ORP values signal high nitrate concentrations, requiring reduced aeration for denitrification; low ORP values indicate high ammonium, requiring increased aeration for nitrification. This control strategy is supported by the findings of Li and Bishop (2002), who demonstrated that ORP provides reliable real-time indication of the metabolic state within activated sludge systems, and by Charpentier et al. (1989), who showed that ORP-based regulation is both more cost-effective and easier to implement than dissolved oxygen-based control. As illustrated in Fig. 4, the cyclic ORP profile between the high and low setpoints produces inverse temporal patterns of NH_4-N and NO_3-N, confirming the simultaneous occurrence of nitrification and denitrification within each aeration cycle, while the concurrent PO_4-P fluctuations indicate enhanced biological phosphorus uptake during the aerobic phase.

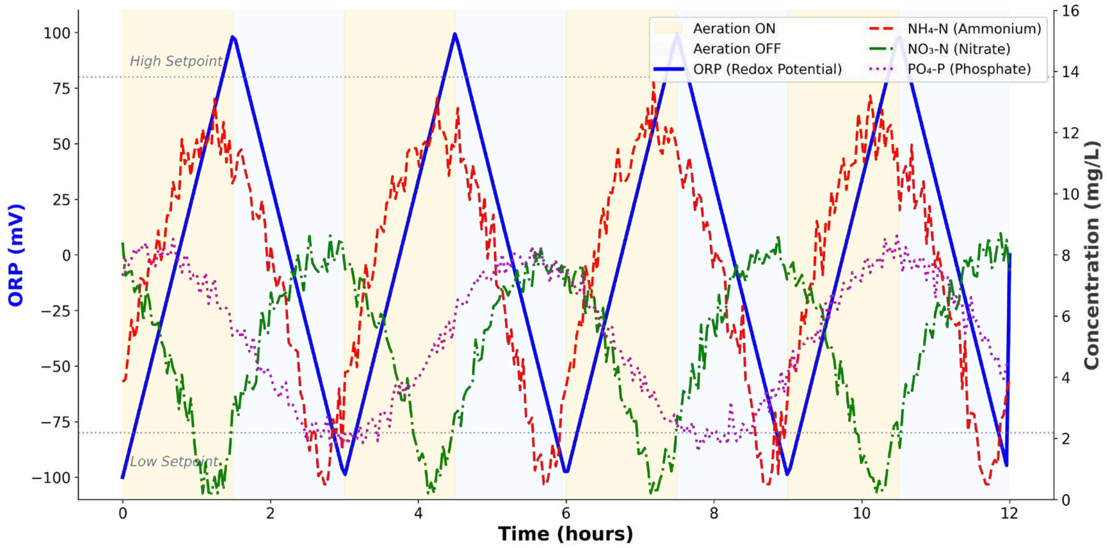

Figure 4: ORP-Controlled Intermittent Aeration - Redox Signal and Nutrient Dynamics

6.2 Aeration Tank Design

The system consists of two aeration tanks, each a 4-channel system with 8.0 m channel width, equipped with two aerators and two propellers per tank. The complete design parameters (Table 4) fall within the extended aeration process criteria documented in Metcalf & Eddy (1991, Table 10-5), which specifies F/M ratios of 0.05-0.15, SRT of 20-30 days, and MLSS of 3,000-6,000 mg/L for conventional extended aeration. However, oxidation ditch variants commonly operate within broader ranges of F/M = 0.05-0.30 and SRT = 10-30 days (WEF/ASCE, 1998). The adopted SRT of 16.9 days positions the Jazan design in a transitional zone between conventional activated sludge and extended aeration, while the F/M of 0.063 remains firmly within the extended aeration range. The non-rounded values of SRT = 16.9 days and HRT = 30.05 hours reflect direct calculation outcomes rather than nominal design choices. The SRT is obtained as the ratio of total mixed-liquor solids inventory to daily waste activated sludge production (25,050 m³ × 3,500 mg/L ÷ 4,676 kg/d ≈ 16.9 d), while the HRT is obtained directly from the aeration volume divided by the Phase 1 design flow (25,050 m³ ÷ 20,004 m³/d × 24 ≈ 30.05 h). The decimal precision is preserved to support reproducibility of the design audit and to highlight that both parameters sit comfortably within the criteria range without margin manipulation.

Table 4: Carrousel Aeration Tank Design Parameters

Parameter	Design Value	Criteria Range
Number of tanks	2	-
Total aeration volume (m³)	25,050	-
F/M ratio (kgBOD/ kgDS·d)	0.063	0.05-0.30
MLSS concentration (mg/L)	3,500	3,000-6,000
HRT (hours)	30.05	18-36
SRT / MCRT (days)	16.9	10-30
Sludge production (kg/d)	4,676	-

6.3 Nutrient Removal Design

The simultaneous nitrogen removal calculations (Table 5) demonstrate adequate denitrification capacity. The influent TKN load of 1,200 kg/d is partitioned into three pathways: 280 kg/d (23.3%) is incorporated into excess sludge biomass, 720 kg/d (60.0%) is biologically nitrified to nitrate, and the remaining total nitrogen in the effluent is maintained at 200 kg/d (16.7%), corresponding to the target effluent TN of ≤ 10 mg/L. In a well-operated nitrification system, this effluent nitrogen would typically comprise residual TKN (NH_4-N + organic N) of approximately 2-4 mg/L and nitrate-nitrogen (NO_3-N) of approximately 6-8 mg/L. The denitrification capacity available (1,100 kg N/d), calculated using the Kayser (1991) correlation (NO_3-Nd/BOD = 0.20), exceeds the requirement (720 kg N/d) by a safety factor of 1.53. This margin is important given the operational variability inherent in ORP-controlled systems (Wareham et al., 1993).

Table 5: Simultaneous Nutrient Removal Design

Parameter	Value	Unit
TKN in excess sludge	280	kg/d
Total N in effluent	200	kg/d
TKN to be nitrified	720	kg/d
Denitrification capacity required	720	kg/d
Denitrification capacity available	1,100	kg/d
TP in effluent	160 (8 mg/L)	kg/d

Fig. 5 illustrates the nitrogen distribution, with 60.0% nitrified, 23.3% removed in excess sludge, and 16.7% remaining as total nitrogen in the effluent, alongside the denitrification balance showing a safety factor of 1.53. The bar charts confirm that all nutrient removal parameters fall within the acceptable design criteria.

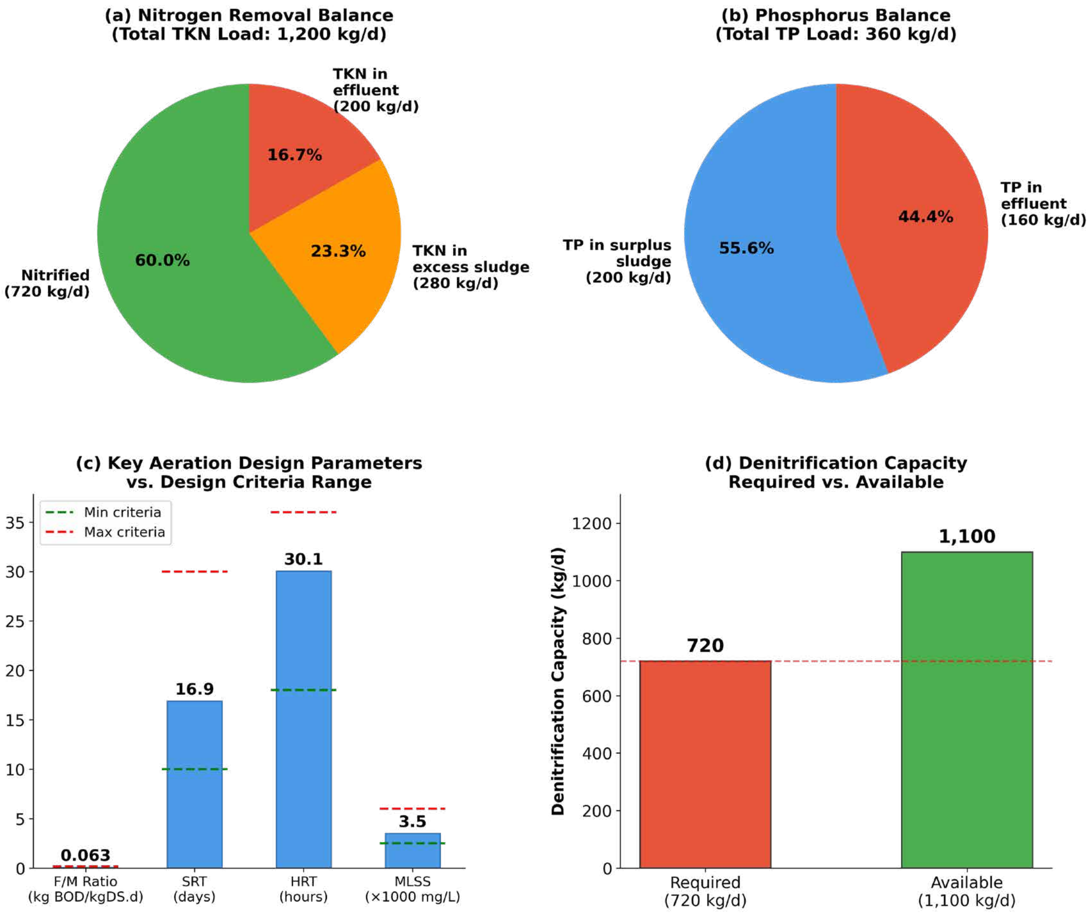

Figure 5: Carrousel Aeration System - Design Analysis

7. Secondary Clarification

Two circular clarifiers (32 m diameter) are provided. Design verification (Table 6) confirms compliance with criteria from Metcalf & Eddy (1991, Table 10-12) and WEF/ASCE (1998).

Fig. 6 confirms that both average (12.44 m³/m²/d) and peak (24.90 m³/m²/d) overflow rates fall within the acceptable range defined by the minimum and maximum criteria, while the grouped bar chart demonstrates that all design values for overflow rates, solids loading, and retention time remain below their respective maximum thresholds, verifying the adequacy of the two 32 m-diameter secondary clarifiers.

Table 6: Secondary Clarifier Design Parameters

Parameter	Design	Min	Max
Tank diameter (m)	32	-	-
Overflow rate avg (m³/m²/d)	12.44	8.14	16.28
Overflow rate peak (m³/m²/d)	24.9	24.42	32.56
Solids loading avg (kg/m²/hr)	2.6	0.97	4.88
Retention time avg (hours)	3.18	2	4

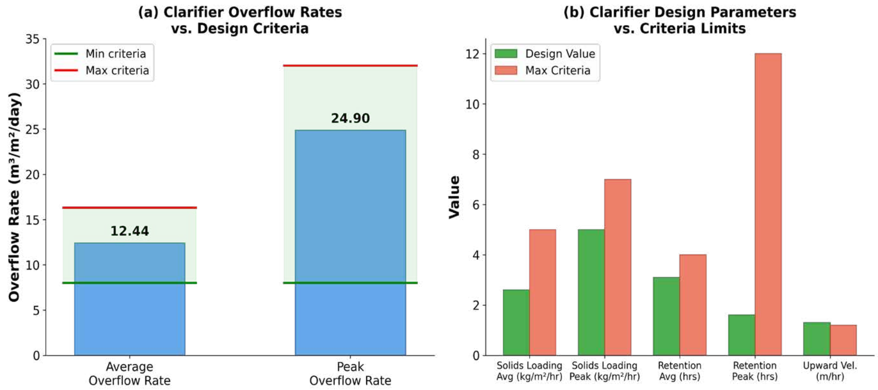

Figure 6: Secondary Clarifier Design Verification

8. Sludge Management

Sludge recycle employs two pumps (2 × 300 L/sec) providing 190% DWF recycle rate. The gravity thickener (13 m diameter) achieves solids loading of 35.23 kg/m²/day, slightly exceeding the upper limit of the recommended range of 24.4-34.2 kg/m²/day for activated sludge thickening per Metcalf & Eddy (1991, Table 12-14), which may necessitate operational monitoring to ensure adequate thickening performance. Retention time of 15.6 hours, while below the 24-hour specification, is sufficient for process requirements.

9. Effluent Disinfection

Two chlorine contact tanks (576 m³ total) provide contact times of 31.1 minutes at average flow and 15.55 minutes at peak flow. Chlorine dosage of 12 mg/L is consistent with the range recommended by the U.S. EPA (1993) for secondary effluent disinfection. Stage I daily chlorine usage is 240.05 kg/day with 30-day storage of 7,201 kg.

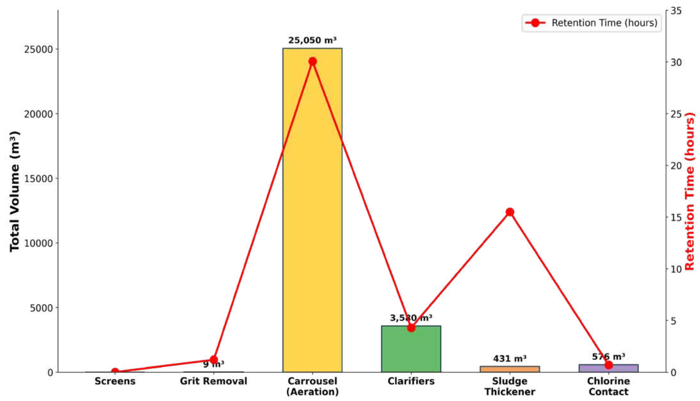

Figure 7: Summary of Unit Process Volumes and Retention Times

Fig. 7 shows the chlorine contact tank volume relative to other treatment units, with the overlaid retention time curve (red line) confirming adequate contact times of 31.1 and 15.55 minutes at average and peak flows, respectively. Fig. 8 compares the daily chemical usage and 30-day storage requirements, highlighting that chlorine dominates consumption at 240.05 kg/d with a corresponding 30-day storage of approximately 7.2 tonnes, consistent with U.S. EPA (1993) recommendations for secondary effluent disinfection.

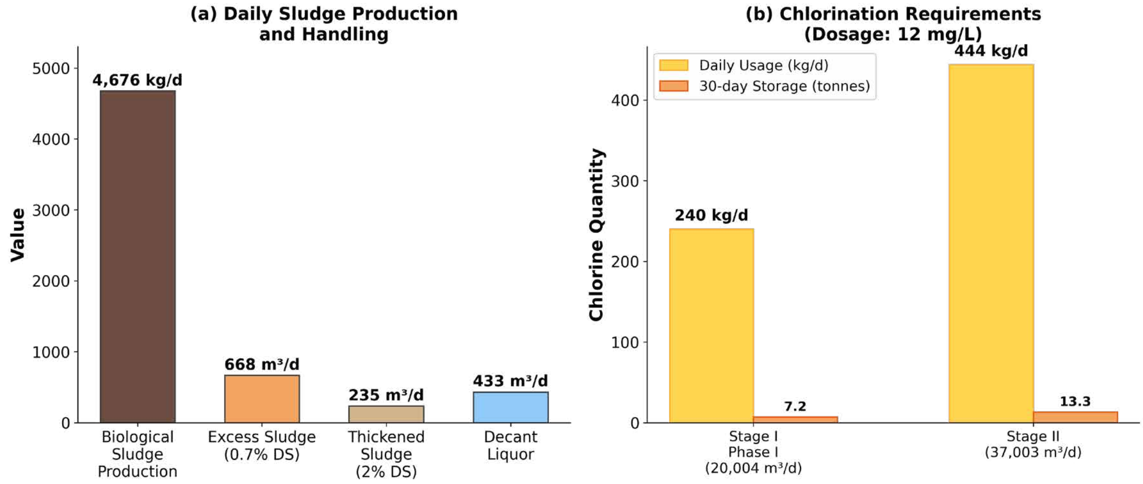

Figure 8: Sludge and Chemical Management

10. Comparison with Previous Studies

10.1 Comparison with Other Carrousel Plants

Table 7 presents a comparative analysis of the Jazan STP design parameters with published data from other Carrousel oxidation ditch installations. The comparison reveals several notable observations regarding the design philosophy adopted for the Jazan facility.

Table 7: Comparative Analysis with Other Carrousel Installations

Parameter	Jazan STP	Wangtang, China	Al-Qateef, KSA	Criteria Range
Flow (m^3/d)	20,004	100,000	45,000	-
Volume (m^3)	25,050	22,000	28,000	-
F/M	0.063	0.05-0.15	0.08-0.12	0.05-0.30
SRT (days)	16.9	12-20	15-25	10-30
HRT (hours)	30.05	5.3	14.9	18-36
MLSS (mg/L)	3,500	3,000-4,000	3,500-4,500	3,000-6,000
TN removal %	83.3	70-85	75-80	60-90

The Jazan STP design is characterized by a notably higher HRT (30.05 hours) compared to the Wangtang WWTP in China (5.3 hours; Xie et al., 2011) and the Al-Qateef plant in Saudi Arabia (14.9 hours; Elsergany, 2014). This conservative approach reflects the extended aeration operating mode that prioritizes sludge stabilization and operational simplicity-an important consideration for smaller municipalities in remote areas of Saudi Arabia where skilled operator availability may be limited.

10.2 Performance Under Arid Climate Conditions

The design of the Jazan STP must be evaluated within the context of arid climate effects. Bachi et al. (2022) demonstrated that activated sludge processes under arid conditions in Algeria achieved biological pollution removal exceeding 90%, with seasonal variation due to temperature effects. Haider et al. (2021) reported similar challenges for wastewater facilities in the Qassim region of Saudi Arabia related to high evaporation rates and elevated influent temperatures.

For the Jazan STP, elevated ambient temperatures (annual average exceeding 30°C) accelerate biological reaction rates but reduce oxygen saturation capacity. Li and Bishop (2002) observed that ORP values at higher water temperatures (20-26°C) were systematically lower than at lower temperatures (14-19°C), due to reduced oxygen saturation and increased microbial oxygen consumption. This finding has direct implications for ORP set-point calibration at Jazan, where water temperatures routinely exceed 25°C. Metcalf and Eddy (2014) note that a 10°C decrease reduces biological reaction rates by approximately half, suggesting the warm Jazan climate provides a kinetic advantage for nitrification and denitrification.

Three coastal-arid factors compound the temperature effect discussed above and deserve explicit attention in the Jazan context. First, proximity to the Red Sea makes the sewer network vulnerable to brackish groundwater infiltration; the observed rise in effluent conductivity from approximately 2,800 µS/cm in 2023 to approximately 5,800 µS/cm in 2024-2025 is consistent with this mechanism and remains below the chloride threshold

(10,000 mg/L) reported by Metcalf & Eddy (2014) for measurable nitrifier inhibition, which is corroborated by the sustained low effluent NH3-N (mean 0.51 mg/L). Second, the very high evaporation rate characteristic of the southern Red Sea coast tends to concentrate dissolved species in open process units, which interacts with the long HRT adopted at Jazan to amplify the apparent salinity gradient between influent and effluent; this provides an a posteriori justification for the conservative HRT, which buffers the biological system against transient salinity excursions. Third, the combination of high air temperature and high relative humidity that prevails on the Jazan coast for much of the year favours volatilisation of free chlorine in open chlorine-contact tanks; the design dose of 12 mg/L (Section 9) therefore represents the upper end of the U.S. EPA (1993) range and is appropriate for the local climatic envelope. Taken together, these coastal-arid considerations confirm that the conservative configuration of the Jazan STP is not merely the legacy of a 1999-era design philosophy, but is well aligned with the specific environmental pressures of its site.

10.3 Nutrient Removal Efficiency Analysis

The anticipated nitrogen removal (83.3%), now confirmed by actual monitoring data showing 91.4% TN removal, compares favorably with Liu et al. (2010), who reported 60-70% TN removal in Carrousel ditches at HRTs of 4-6 hours. The higher removal at Jazan is attributable to: (1) the significantly longer HRT (30.05 hours); (2) ORP-controlled intermittent aeration optimizing nitrification-denitrification balance; and (3) favorable temperature regime enhancing both nitrifier and denitrifier activity.

While the design anticipated only 55.6% phosphorus removal (effluent TP of 8 mg/L) through biological uptake alone, actual monitoring reveals 88.7% removal (mean effluent TP of 2.04 mg/L), indicating effective EBPR under ORP-controlled conditions. Elsergany (2014) demonstrated that the Al-Qateef Carrousel plant required supplemental chemical treatment with alum (50 mg/L) to achieve effluent TP below 1 mg/L, suggesting similar polishing may be necessary at Jazan should future regulations become more stringent.

10.4 Design Methodology Evaluation

The empirical, criteria-based design approach was standard practice in 1999 but has since been supplemented by dynamic process modeling using frameworks such as the IWA Activated Sludge Model (ASM) series. Xie et al. (2011) demonstrated that ASM2d integration with optimization algorithms can significantly improve Carrousel performance. Future upgrades at Jazan would benefit from calibrated process modeling to optimize ORP control set-points and intermittent aeration cycling patterns.

11. Operational Performance Validation

To validate the design calculations against actual plant performance, effluent monitoring data were compiled from the Jazan STP laboratory records over a 29-month span from January 2023 to July 2025. The 29-month window was not selected as a target duration; it represents the entire set of consecutive monthly monitoring records that were available, validated, and released by the plant's laboratory at the cut-off date for this analysis (July 2025). A round 30-month or 2.5-year window was not used because it would have required either including August 2025 data, which had not yet been validated by the plant's quality-control protocol at the time of submission, or excluding July 2025 to retain a 28-month round window, which would have unnecessarily discarded one validated reporting cycle. Retaining all 29 validated months therefore preserves the maximum statistical information from the operational record while remaining fully traceable to the plant's certified data. Monthly composite samples were analyzed for 16 physicochemical parameters including pH, temperature, BOD5, COD, TSS, dissolved oxygen, MLSS, ammonia-nitrogen, nitrate-nitrogen, nitrite-nitrogen, total phosphorus, turbidity, conductivity, TDS, free chlorine, and oil and grease. Table 8 presents the summary statistics of the key effluent quality parameters, while Table 9 compares the actual performance against the original design targets.

Table 8: Effluent Monitoring Data Summary

Parameter	Unit	Mean	Min	Max
pH	-	7.38	7.05	7.65
Temperature	°C	29.95	26.18	33.32
BOD_5	mg/L	4.19	2.04	10.52
COD	mg/L	14.35	6.83	39.06
TSS	mg/L	2.77	1.00	10.74
DO	mg/L	5.54	3.84	6.64
MLSS	mg/L	3,528	3,159	3,811
NH_3-N	mg/L	0.51	0.07	3.84
NO_3-N	mg/L	4.53	1.11	7.08
NO_2-N	mg/L	0.15	0.01	0.26
Total Phosphorus	mg/L	2.04	0.03	6.86
Turbidity	NTU	1.42	0.59	3.34
Conductivity	µS/cm	4,541	2,349	6,017
TDS	mg/L	3,094	1,355	4,653

Table 9: Design Targets versus Actual Operational Performance

Parameter	Design Influent (mg/L)	Design Effluent (mg/L)	Actual Effluent (mg/L)	Design Removal %	Actual Removal %
BOD_5	275	≤ 25	4.19	90.9	98.5
COD	550	-	14.35	-	97.4
TSS	275	≤ 25	2.77	90.9	99.0
Total N	60	≤ 10	5.19	83.3	91.4
Total P	18	≤ 8	2.04	55.6	88.7

The operational data reveal that the Jazan STP consistently exceeds its design performance targets across all parameters. Most notably, the actual total phosphorus removal of 88.7% substantially surpasses the design-anticipated 55.6%, suggesting that the ORP-controlled intermittent aeration regime effectively promotes enhanced biological phosphorus removal (EBPR) by creating alternating anaerobic-aerobic conditions favorable for phosphorus-accumulating organisms (PAOs). However, the TP effluent (mean 2.04 mg/L) still exceeds the current MWE (2006) standard of ≤ 1 mg/L for unrestricted reuse, confirming that supplementary chemical polishing remains necessary for full regulatory compliance. The mean effluent total nitrogen of 5.19 mg/L, well below the 10 mg/L design target, demonstrates effective simultaneous nitrification-denitrification, with effluent nitrogen dominated by NO_3-N (mean 4.53 mg/L) and minimal residual ammonia (mean 0.51 mg/L), indicating robust nitrification performance. The MLSS concentration averaged 3,528 mg/L, closely matching the design value of 3,500 mg/L, confirming appropriate biomass management. A distinct performance shift is observed between 2023 and 2024-2025, with BOD_5 decreasing from a 2023 mean of approximately 8.3 mg/L to approximately 2.5 mg/L in 2024-2025, potentially reflecting operational optimization or improved influent quality over time.

12. Discussion

The selection of the Carrousel system with ORP-controlled intermittent aeration represents an appropriate technology choice for Jazan. The extended aeration mode (F/M = 0.063, SRT = 16.9 days) provides excellent BOD removal and sludge stabilization, while ORP control enables efficient biological nutrient removal without separate anoxic zones. The calculated denitrification safety factor of 1.53 provides adequate operational margin.

Critically benchmarked against regulatory standards and published full-scale data, the validated performance of the Jazan STP can be interpreted along three axes. (i) Against the MWE (2006) unrestricted-reuse standard (BOD5 ≤ 10, TSS ≤ 10, TN ≤ 10, TP ≤ 1 mg/L), the plant comfortably satisfies all parameters except TP (mean 2.04 mg/L); even so, the actual TP performance halves the design-anticipated 8 mg/L, demonstrating that ORP-controlled intermittent aeration delivers measurable EBPR benefit even where no separate anaerobic selector was provided. (ii) Against published Carrousel installations, the Jazan TN removal of 91.4 % exceeds the 70-85 % range reported at Wangtang, China (Xie et al., 2011) and the 75-80 % range at Al-Qateef, Saudi Arabia (Elsergany, 2014), as well as the 60-70 % range reported by Liu et al. (2010) for low-HRT Carrousel SND. The differential is consistent with the substantially longer HRT (30.05 h vs. 5.3 and 14.9 h, respectively), confirming that the conservative hydraulic configuration translates directly into a measurable nutrient-removal advantage. (iii) Against the dynamic-modelling benchmarks of Yang et al. (2011) and Xie et al. (2011), the empirical, criteria-based design adopted at Jazan in 1999 has nonetheless converged on operating set-points that recent ASM2d optimisation studies retrospectively endorse for warm-climate Carrousel systems. This convergence indicates that the inclusion of operational ORP feedback in the original design provided robustness comparable to that obtained, in more recent studies, through dynamic model calibration.

The ORP-controlled intermittent aeration strategy offers significant energy optimization potential compared to conventional continuous aeration. Charpentier et al. (1989) showed that ORP-based control reduces energy consumption while maintaining treatment performance. Chang and Hao (1996) reported that pH/ORP dual control achieved energy savings with average aeration ratios of 0.23 versus 0.33-0.50 for fixed-time systems. The use of propellers for flow velocity maintenance during aerator-off periods is offset by elimination of internal recirculation pumps required in conventional pre-denitrification configurations.

The design effluent targets (BOD ≤ 25 mg/L, SS ≤ 25 mg/L) were consistent with 1999 standards. However, the 2006 MWE guidelines require BOD5 and TSS not to exceed 10 mg/L for unrestricted agricultural irrigation (Al-Jasser, 2011). Meeting these would require tertiary treatment upgrades at the Jazan STP, as demonstrated at the Al-Qateef plant where sand filters were added (Elsergany, 2014).

The secondary clarifiers demonstrate conservative design with all parameters within established criteria.

The sludge thickener retention time of 15.6 hours, while below the 24-hour specification, is a practical compromise reflecting the available tank diameter and follows the solids loading guidelines from Metcalf & Eddy (1991, Table 12-14) for air-activated sludge thickening.

12.1 Sensitivity Considerations

The design calculations presented herein are based on average influent loading conditions and steady-state assumptions. In practice, several factors may affect actual performance. During peak flow conditions (2:1 peaking factor), the HRT decreases to approximately 15 hours and the clarifier overflow rate doubles to 24.9 m³/m²/d, which may temporarily reduce effluent quality. The elevated ambient temperatures in Jazan (annual average exceeding 30°C) accelerate biological kinetics but simultaneously reduce oxygen saturation capacity from approximately 8.4 mg/L at 25°C to 7.6 mg/L at 35°C, affecting ORP response characteristics and potentially requiring seasonal adjustment of aeration set-points. Furthermore, coastal groundwater infiltration into the sewer network may introduce elevated salinity into the influent, which can inhibit nitrifying bacteria at chloride concentrations exceeding 10,000 mg/L (Metcalf & Eddy, 2014). The operational monitoring data support this concern, showing a marked increase in effluent conductivity from a 2023 mean of approximately 2,800 µS/cm to approximately 5,800 µS/cm in 2024-2025, with TDS rising correspondingly from approximately 2,000 to 4,000 mg/L, warranting investigation into potential groundwater infiltration sources. These operational variables underscore the importance of adaptive ORP control and regular process monitoring. Compared with the sensitivity ranges reported in the recent literature for similar systems, the observed Jazan responses fall within expected envelopes: Bachi et al. (2022) documented temperature-driven seasonal removal swings of 5-10 % in activated sludge plants operated under arid Algerian conditions; Navada and Vadstein (2022) showed that nitrification capacity declines sharply only above the brackish-water salinity range, a level above the equivalent salinity inferred from the conductivity record at Jazan; and Owaes et al. (2024) reported that real-time control schemes coupling redox potential and pH tolerate seasonal variation without significant set-point recalibration, provided the SRT remains sufficient to sustain a stable nitrifier population. The Jazan SRT of 16.9 d therefore lies comfortably within this operational envelope, which is consistent with the observation that the 29-month effluent record shows no statistically meaningful nitrification breakthrough despite the documented salinity rise.

12.2 Limitations

Several limitations of this study should be acknowledged. First, while 29 months of effluent monitoring data have been incorporated to validate the design analysis, the available dataset does not include concurrent influent quality measurements; therefore, the removal efficiencies presented assume that actual influent concentrations are consistent with the design values. Systematic influent-effluent paired sampling would enable more precise efficiency calculations. Second, the comparative analysis is limited to two Carrousel installations (Wangtang and Al-Qateef), which constrains the generalizability of the benchmarking conclusions. A broader comparison with additional plants in arid coastal settings would strengthen the findings. Third, the analysis employs steady-state, empirical design methods rather than dynamic process simulation using calibrated ASM models, which would provide more accurate predictions of performance variability under transient loading conditions. These limitations are not unique to the present work: Alhajri et al. (2025) reported that fewer than 15 % of operational performance reports for Saudi WWTPs include paired influent-effluent records, and Owaes et al. (2024) noted that long-term validation windows for ORP-controlled aeration studies remain comparatively rare in the peer-reviewed literature. The 29-month dataset compiled here therefore already provides one of the longer published validation windows for a Carrousel system in a hot-arid coastal setting; nevertheless, extending the analysis to a full five-year cycle with paired influent-effluent sampling, ideally coupled with calibrated ASM2d modelling along the lines of Xie et al. (2011), would constitute the most informative next step.

13. Conclusions

This paper has presented a comprehensive process design analysis of the Jazan STP. The following conclusions are drawn:

1. The Carrousel system with total aeration volume of 25,050 m³, operating at F/M of 0.063 and SRT of 16.9 days, achieves effluent BOD and SS of 25 mg/L or below, consistent with the design criteria documented in Metcalf & Eddy (1991) and WEF/ASCE (1998).
2. ORP-controlled intermittent aeration enables simultaneous nitrification-denitrification, with available denitrification capacity (1,100 kg N/d) exceeding requirements (720 kg N/d) by 53%. The anticipated effluent TN of ≤ 10 mg/L compares favorably with published results from similar facilities (Liu et al., 2010; Xie et al., 2011).
3. The Jazan STP design, when compared with the Wangtang WWTP (China) and Al-Qateef WWTP (Saudi Arabia), demonstrates a more conservative approach characterized by longer HRT, which prioritizes operational stability and sludge mineralization.

4. **4.** Under the arid climate of the Jazan Region, elevated temperatures provide kinetic advantages for biological treatment but require careful calibration of ORP set-points due to temperature-dependent effects on redox measurements (Li & Bishop, 2002).
5. **5.** Operational monitoring over 29 months validates the design, with actual BOD_5 removal of 98.5%, TSS 99.0%, TN 91.4%, and TP 88.7%, indicating effective enhanced biological phosphorus removal under ORP-controlled aeration.
6. **6.** The design methodology, validated by operational data, provides a technical reference for similar projects in arid coastal regions, though future expansions would benefit from ASM-based dynamic modeling.

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