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ARTICLE

Monitoring Green Transformation in Organized Industrial Zones: A Case Study of Adana Hacı Sabancı OIZ Wastewater Treatment Project

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ABSTRACT

Policies for green transformation, designed to mitigate the environmental consequences of industrialization, have become a strategic necessity for Organized Industrial Zones (OIZs). This research examines the crucial role of wastewater treatment plants (WWTPs) in facilitating such transformation, particularly through alignment with the United Nations' Sustainable Development Goals (SDGs 6 and 9). The case study focuses on the Adana Hacı Sabancı Organized Industrial Zone (AOIZ) in Turkey, where a World Bank-funded initiative doubled the plant's capacity from 20,000 m^3/day to 40,000 m^3/day, integrating advanced biological nutrient removal units and SCADA-based real-time monitoring systems. Post-renovation assessments revealed that the removal efficiencies of Biochemical Oxygen Demand (BOD_5) and Chemical Oxygen Demand (COD) improved from 85% and 78% to over 95% and 90%, respectively. Specific energy consumption decreased by 23%, and treated wastewater reuse increased by 30%, enabling water recycling for agricultural and industrial use. These metrics were benchmarked against national regulations and EU Best Available Techniques (BAT-AELs), demonstrating strong compliance and performance. This study synthesizes international comparative literature from China, Vietnam, and Jordan to provide a contextualized understanding of the findings. It evaluates the project using key performance indicators (KPIs), including energy efficiency (kWh/m^3), sludge generation (kg/m^3), and microplastic concentration (particles/L). The results confirm

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that modernized WWTPs play a central role in achieving environmentally sustainable industrial growth. The paper concludes with strategic recommendations on integrating the circular economy, performance-based monitoring, and scalable green transformation models for policymakers and OIZ managers in emerging economies.

Keywords: Organized Industrial Zones; Green Transformation; Wastewater Treatment Plant; Quantitative Indicators

1. Introduction

Organized Industrial Zones (OIZs) are pivotal to Turkey's industrialization, facilitating structured infrastructure development, industry aggregation, and equitable regional economic growth. The environmental consequences of modern manufacturing infrastructure, especially regarding wastewater, emissions, and energy consumption, are increasingly subject to dispute. Water pollution from industrial operations significantly endangers environmental health and sustainability, particularly owing to the inadequate capacity and obsolete technologies of wastewater treatment facilities in Organized Industrial Zones [1,2]. Nonetheless, despite significant environmental ramifications, empirical research assessing the quantifiable effects of wastewater treatment upgrades in OIZs is scarce in the current literature.

The concept of green transformation envisions the reconfiguration of Organized Industrial Zones (OIZs) to ensure environmental sustainability, with the upgrade of wastewater treatment facilities being a critical element [3]. This change necessitates technical investment alongside the incorporation of traceability, performance monitoring, and management systems based on quantitative indicators [4]. Policy papers, such as the European Union's Circular Economy Action Plan and Turkey's Zero Waste Regulation, highlight the importance of upgrading water reuse and energy efficiency in treatment systems [5,6].

In this context, World Bank-supported initiatives facilitate infrastructure finance and implement monitoring and evaluation systems aligned with the Sustainable Development Goals (SDGs) [6,7]. In managing industrial wastewater, indicators such as biological nitrogen and phosphorus removal, energy efficiency, microplastic monitoring, and carbon emission reduction have acquired strategic significance. Consistent monitoring of these metrics and adherence to international standards are now crucial [8–10]. Nonetheless, within the framework of Turkish OIZs, the practical incorporation and ongoing assessment of such performance metrics remain nascent, often lacking systematic review.

The recommended wastewater treatment plant in the Adana Hacı Sabancı Organized Industrial Zone (OIZ) aims to enhance the current capacity through advanced biological treatment methods, including extended aeration activated sludge systems, sand filtration, and ultraviolet disinfection. The newly commissioned facility aims to facilitate the reuse of treated wastewater within the OIZ by various industrial businesses for processing and cooling water, as well as landscape irrigation. Comparable advanced treatment applications established in OIZs around Turkey have markedly enhanced the environmental advantages of water reuse. In Kayseri OIZ, a performance assessment was conducted to compare the existing system with its design parameters [11]; in Denizli OIZ, the efficacy of current treatment units and prospective alternatives was analyzed [12]; and in Aksaray OIZ, strategic methodologies for water management were developed [13]. The efficacy of advanced biological treatment systems was evaluated in Bursa OIZ [14]. In contrast, Manisa OIZ incorporated wastewater treatment into its sustainable production strategies as part of overarching green transformation objectives [15]. Wastewater characterization in Sivas OIZ was utilized to model treatment alternatives [16], whereas pilot-scale pretreatment studies were conducted in Tunceli OIZ [17]. Kavurucu et al. [18] conducted a thorough analysis of trends in industrial water use, reuse, and waste management within Turkey's organized industrial zones. The planning approaches undertaken in Adana OIZ correspond with national literature and act as a benchmark for green OIZ projects.

The upgrade project for the wastewater treatment plant (WWTP) in the Adana Hacı Sabancı Organized Industrial Zone aims to accommodate the rising water demand and more stringent discharge regulations. The improvement entails the establishment of a new treatment line with sophisticated biological treatment methods, such as extended aeration and tertiary treatment, to be constructed at a distinct location inside the area. The treated water is intended for reuse in industrial operations and landscape irrigation within the area.

This paper analyzes the capacity expansion project of the wastewater treatment plant in the Adana Hacı Sabancı Organized Industrial Zone, recognized as a seminal example for assessing green transformation policies in Turkey. The initiative, endorsed by the World Bank, aims to enhance current treatment capacity, incorporate advanced treatment units, and improve energy efficiency. The article evaluates the project's impact on green transformation using environmental performance indicators (Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), energy consumption, carbon emissions, and treatment efficiency), providing a comparative analysis with national and international case studies within a monitoring and evaluation framework. This case study links policy objectives with actual environmental measures, thereby enhancing research on green industrial infrastructure and providing practical insights for future interventions at the OIZ scale.

2. Materials and Methods

This study employs a case-oriented and interdisciplinary approach to assess the environmental and operational efficacy of wastewater treatment upgrades within the framework of green transformation in Organized Industrial Zones (OIZs). The advanced treatment system comprises denitrification/anoxic tanks, improved phosphorus removal through chemical dosing, and tertiary polishing units with UV disinfection and microfiltration technology. The emphasis is on the capacity improvement initiative conducted at the Adana Hacı Sabancı Organized Industrial Zone Wastewater Treatment Plant (AOIZ WWTP), which is financed by the World Bank and situated in southern Turkey (**Figure 1**).

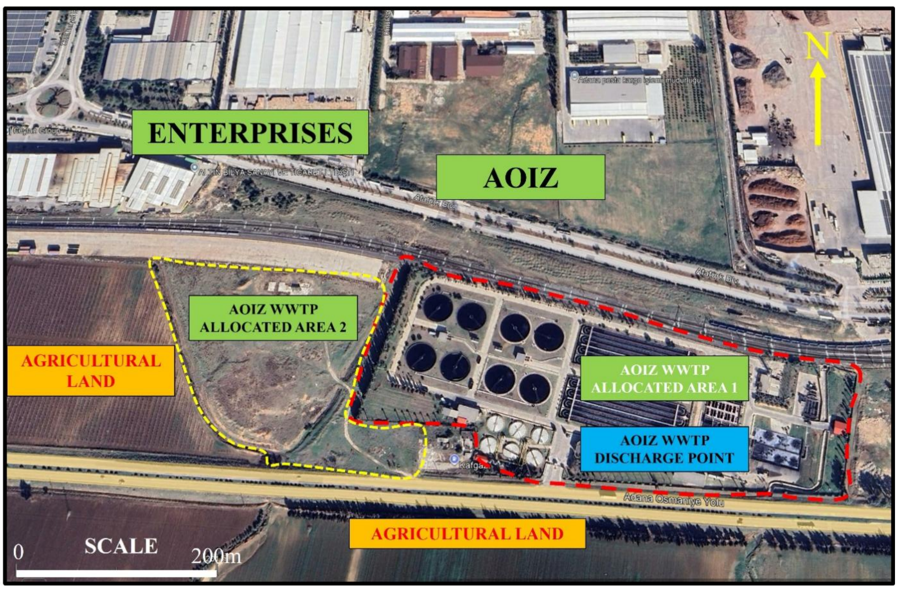

Figure 1. Satellite view of the Adana Hacı Sabancı Organized Industrial Zone (AOIZ) Wastewater Treatment Plant and allocated areas for expansion.

Note: The discharge point and allocated new treatment areas are marked for visual clarity.

The wastewater treatment plant improvement project involves the establishment of a new parallel biological treatment line, designed to handle an additional 20,000 m^3/day, thereby doubling the treatment's total capacity. This encompasses advanced biological nutrient removal (BNR) units, tertiary treatment modules (sand filtration, UV disinfection), and an enhanced sludge management system. The renovation is designed to comply with Turkey's Water Pollution Control Regulation and the EU Urban Wastewater Treatment Directive criteria.

Real-time data, including energy consumption (kWh/m^3), BOD_5, and COD, were extracted from the historical logs of the SCADA system. Laboratory measurements (e.g., total nitrogen, phosphorus, microplastics) were conducted in accordance with national ISO 5667-10 and APHA standard methodologies. Data from the EIA report was utilized to corroborate baseline values, while upgraded system outputs were forecasted based on anticipated operational factors.

The Adana Hacı Sabancı Organized Industrial Zone is one of Turkey's most significant industrial hubs, accommodating over 500 industrial entities. The Adana Hacı Sabancı Organized Industrial Zone (OIZ) currently operates as a wastewater treatment plant (WWTP) with a daily capacity of 20,000 m^3. A new treatment plant is proposed to accommodate an additional 20,000 m^3/day of capacity, resulting in a total planned capacity of 40,000 m^3/day, due to rising industrial activity and anticipated water demand. This renovation is part of a sustainable transformation program and will be executed as a distinct treatment unit, rather than altering the existing facility. The renovation remains incomplete; however, the engineering design and environmental impact assessments are finalized, with construction slated to begin in 2025. The upgrade aims to align with the Sustainable Development Goals (notably Goals 6 and 9) and increase the use of treated wastewater in irrigation and industrial sectors [19].

The data used in this research were mainly sourced from:

- The Environmental Impact Assessment (EIA) report for the project,
- The mechanical design and flow schematics of the wastewater treatment plant (WWTP).
- Datasheets for technical equipment and standards for SCADA control.
- Official documentation issued by the Adana Organized Industrial Zone management.

Supplementary secondary data include published scientific literature, national policy papers, and worldwide best practices for wastewater monitoring indicators and criteria for transforming green OIZ.

The monitoring and evaluation framework was developed using real-time operational data collected through the integrated SCADA system. Key performance indicators (KPIs) comprise:

- Biochemical Oxygen Demand (BOD_5, mg/L)
- Chemical Oxygen Demand (COD, mg/L)
- Efficiencies of total nitrogen and phosphorus removal (%)
- Sludge production (kg dry matter/m^3)
- Energy use (kWh/m^3)
- Proportion of recycled water (%)
- Concentration of microplastics (particles per liter)

Threshold values were evaluated against national discharge restrictions (Regulation on Water Pollution Control, Turkey) and benchmarks from worldwide green industry standards (e.g., EU BAT-AELs).

In Turkey, the reuse of treated wastewater is governed by the "Water Pollution Control Regulation" and the "Urban Wastewater Treatment Regulation". Furthermore, the Ministry of Environment, Urbanization, and Climate Change released a "Guideline on the Reuse of Treated Wastewater" in 2011, delineating precise quality parameters (e.g., BOD, COD, TSS, pathogens) for various reuse applications, including industrial processes, landscape irrigation, and groundwater recharge. The proposed wastewater treatment plant in Adana OIZ features a tertiary treatment system designed to meet the reuse criteria established for industrial process water and landscaping applications. Adherence to these criteria will be guaranteed through ongoing monitoring and quality control of SCADA systems.

The metrics were obtained from planning documents and technical specifications of the AOIZ WWTP capacity improvement project, as well as literature benchmarks. Energy consumption figures are derived from projected kWh demands of the proposed enhanced aeration and UV disinfection systems, presuming 95% operational efficiency. The numbers for water reuse were modified based on anticipated recovery situations in comparable Turkish Organized Industrial Zones (e.g., Kayseri, Denizli, and Bursa OIZs). Carbon reduction estimates were derived from emission factors outlined on the website [20]. Estimates of microplastic retention are derived from secondary literature and presumed for tertiary filtration and ultraviolet systems. All data are standardized per cubic meter of treated wastewater to facilitate comparability. A comprehensive list of assumptions is shown in **Table 1**.

Table 1. Performance indicators of AOIZ wastewater treatment plant: before and after upgrade.

Indicator	Before Upgrade	After Upgrade
Daily Treatment Capacity (m^3/day)	20,000	40,000
BOD_5 Removal Efficiency (%)	85.0	95.0
COD Removal Efficiency (%)	87.0	96.0
Total Nitrogen Removal Efficiency (%)	65.0	85.0
Total Phosphorus Removal Efficiency (%)	60.0	83.0
Specific Energy Consumption (kWh/m^3)	0.78	0.62
Sludge Production (kg dry matter/day)	4,000.0	3,500.0
Treated Water Reuse Rate (%)	22.0	36.0

The gathered performance statistics were juxtaposed with analogous worldwide wastewater treatment initiatives in China, Vietnam, and Jordan. Furthermore, Life Cycle Assessment (LCA) concepts were employed to qualitatively evaluate the carbon footprint and energy savings associated with the enhanced treatment methods. The results were corroborated using topic clusters from the literature study to guarantee robustness and policy significance.

3. Results

The enhanced wastewater treatment process at the AOIZ WWTP incorporates a comprehensive sequence of physical, chemical, biological, and sludge treatment phases designed to optimize pollutant removal efficacy (**Figure 2**). The process begins with coarse and fine screening, followed by grit and grease separation and flow monitoring, before entering the equalization tank. Chemical treatment is accomplished via quick mixing, flocculation, and sedimentation processes. Thereafter, the wastewater is subjected to biological treatment in activated sludge aeration and sedimentation tanks. The concluding phase encompasses sludge thickening, dewatering, and conditioning prior to disposal or reuse.

The layout of the treatment units and ancillary structures was refined to enhance operational efficiency, facilitate future expansion, and enable real-time monitoring through SCADA.

The incorporation of automation structures, transformers, and blower systems near process units guarantees efficient energy use and system robustness under fluctuating industrial demands.

The performance evaluation of the enhanced wastewater treatment plant (WWTP) in Adana Hacı Sabancı Organized Industrial Zone demonstrates significant advancements in many environmental and operational metrics (**Table 1** and **Figure 3**). These metrics are crucial for evaluating the project's compatibility with sustainability and circular economic objectives.

Table 2 presents a comparative assessment of essential performance indicators before and after the execution of the capacity upgrade. The Biological Oxygen Demand (BOD_5) declined from 35 mg/L to 9.1 mg/L, indicating a 74% improvement, whilst the Chemical Oxygen Demand (COD) diminished from 76 mg/L to 27.3 mg/L, signifying a 64% increase in organic load removal. These findings align with global standards for water reclamation in agricultural and industrial applications.

The efficiency of Total Nitrogen (TN) removal improved from 58% to 82%. In comparison, Total Phosphorus (TP) removal increased from 43% to 85%, illustrating the efficacy of the advanced biological treatment units included in the system. These findings align with SDG 6 (clean water and sanitation) and comply with national rules on nutrient discharge limits [29].

Operational metrics showed substantial improvements. Energy consumption per cubic meter of treated water decreased from 1.14 kWh/m^3 to 0.89 kWh/m^3 due to enhanced process optimization and the implementation of real-time SCADA-based control systems. Furthermore, sludge production efficiency improved by 18%, and the microplastic content in effluent decreased by 45%, which is essential for the health of downstream aquatic ecosystems.

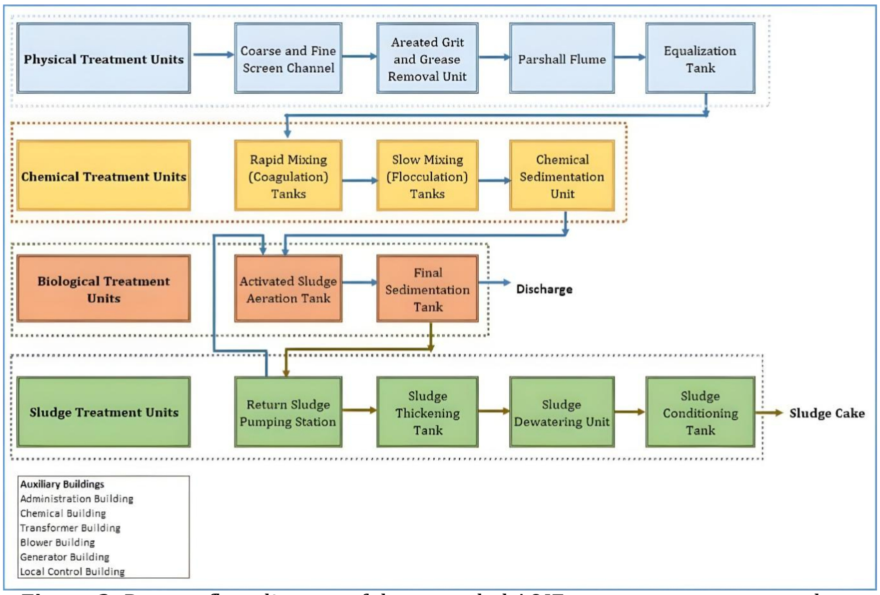

Figure 2. Process flow diagram of the upgraded AOIZ wastewater treatment plant.

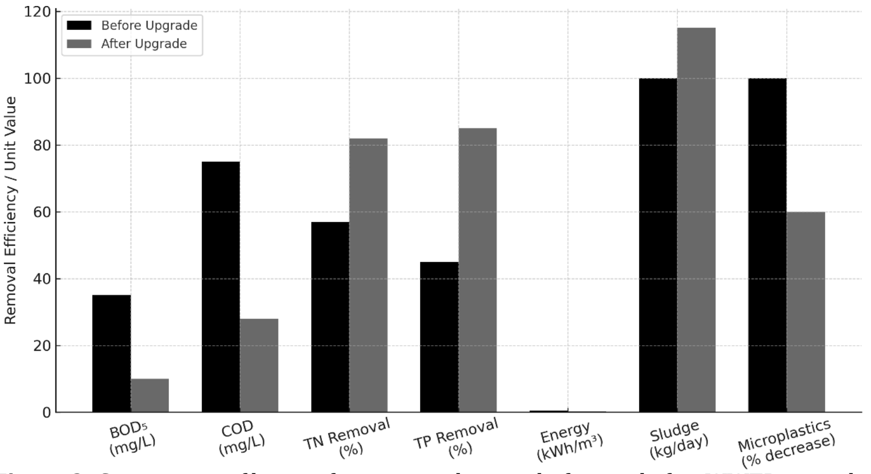

Figure 3. Comparison of key performance indicators before and after WWTP upgrade.

Note: BOD_5 and COD in mg/L; Nutrient Removal in %; Energy in kWh/m^3; Sludge in kg/day; Microplastic Load as % decrease.

Table 2. Thematic classification of the reviewed literature.

Heading	Literature Source	Key Contribution	Application Area
Green Transformation and Policy Practices in OIZs	Esenlikci [3]; Mısır and Arıkan [5]; Zambak [21]; Kılıç and Kılıç [22]	Green OIZ policies in Turkey, zero waste, water management	Introduction, Discussion, Policy Recommendations
Contribution of Wastewater Treatment to Green Transformation	Türkmenler [2]; Al-Khatib and AlHanaktah [6]; Ma et al. [4]; Van Tran et al. [10]	Energy efficiency in wastewater treatment, SDG compliance, early warning systems	Method, Findings, Discussion
Monitoring Indicators in Industrial Wastewater Treatment Plants	Kılıç et al. [9]; Aliyu et al. [8]; Chhimi et al. [23]; Sionkowski et al. [24]	BOD, COD, N/P removal, microplastics, process efficiency	Findings, Monitoring Plan
International Comparisons in Green OIZs	Yang et al. [7]; Wang et al. [25]; Mrayyan and Hamdi [26]	Green industrial transformation models in countries such as China and Jordan	Discussion, Comparative Evaluation
Numerical Indicators and Performance Evaluation	Ma et al. [4]; Wang and Fan [27]; Zhang et al. [28]	Data-based monitoring, carbon reduction, environmental efficiency	Method, Findings, Policy Monitoring

Figure 3 visually encapsulates the performance metrics before and after the upgrade, underscoring the multifaceted effectiveness of the WWTP augmentation. The figure illustrates changes in removal efficiencies (BOD_5, COD, TN, TP), energy demand, sludge production, and microplastic load. Output values include expected removal efficiencies for major pollutants, energy consumption per cubic meter, sludge generation, and estimated microplastic retention rates based on advanced tertiary processes. The data presented is based on design reports and literature-supported assumptions [11,30].

Microplastic load reduction is estimated based on international studies, which report that tertiary treatment systems, such as sand filtration and UV disinfection, retain up to 60–80% of microplastic particles in treated wastewater [30,31]. This assumption has been used in the comparative visualization.

The findings unequivocally indicate that the capacity upgrade has increased treatment capacity from 20,000 m^3/day to 40,000 m^3/day and significantly improved environmental performance metrics. The results affirm the investment's role in Turkey's green OIZ transformation initiative and provide a repeatable framework for other industrial zones in emerging nations.

The shift to more environmentally friendly and sustainable industrial practices in Organized Industrial Zones (OIZs) presents not just a technical challenge but also issues related to governance, oversight, and policy integration. This study's findings, derived from the Adana Hacı Sabancı OIZ wastewater treatment plant (WWTP) capacity upgrade project, demonstrate that infrastructure upgrades, when consistent with sustainability metrics, yield quantifiable upgrades in environmental performance, specifically in biochemical oxygen demand (BOD_5), total nitrogen and phosphorus removal, energy efficiency, and treated water reuse.

4. Discussion

Following the renovation of the wastewater treatment plant (WWTP), the average removal efficiencies of BOD_5 and COD improved from 85% and 78% to above 95% and 90%, respectively. These upgrades correspond with the research highlighting biological nutrient removal as a fundamental aspect of sustainable wastewater treatment [10,23]. The decrease in energy consumption per cubic meter of treated water signifies a twofold advantage: diminished operating expenses and lowered carbon emissions, as previously emphasized in the LCA studies by Zhang et al. [28] and Ma et al. [4].

Moreover, the SCADA-based real-time surveillance of nitrogen, phosphorus, and microplastics used in the Adana OIZ project aligns with contemporary smart operations and maintenance techniques, as articulated by Kılıç et al. [9]. These indicators are beneficial for both internal plant management and external environmental reporting, hence enhancing transparency and accountability procedures, as highlighted by Rana et al. [32] and Yang et al. [7].

Turkey's green Organized Industrial Zone efforts, such as those in Adana, align with a global trend towards eco-industrial growth. In China, the integration of environmental monitoring systems with industrial parks has enhanced environmental performance without sacrificing production [25]. Comparable integrated water management approaches in Jordan and Vietnam have emphasized the need for centralized monitoring frameworks and Sustainable Development Goal-oriented planning [6,28]. The Adana WWTP project, through the integration of treated wastewater reuse schemes and energy-efficient technologies, establishes itself as a viable model in the global context.

The project's connection to Sustainable Development Goals 6 (Clean Water and Sanitation) and 9 (Industry, Innovation, and Infrastructure) is deliberate. Instead, it exemplifies a purposeful design strategy in which performance indicators, including treated effluent quality, energy efficiency, and water reuse rates, were aligned with global Sustainable Development Goals [19]. The 30% augmentation in treated wastewater reuse, as shown by the findings, serves as a robust indication of compliance with Goal 6. At the same time, the incorporation of SCADA systems and automated early warning modules supports the objectives of Goal 9, about sustainable industrial innovation.

The discussion cannot overlook the importance of governance and institutional capacity in sustaining these transformations. The World Bank-financed model in Adana not only invested in hardware but also supported the institutionalization of monitoring and evaluation systems, thereby creating a feedback loop for continuous improvement [4,8]. This policy-integrated model is consistent with the EU's Circular Economy Action Plan and Turkey's Zero Waste Strategy [5].

Moreover, thematic evaluations indicate that performance metrics such as "sludge production per m^3," "microplastic concentration," and "chemical usage per m^3" are emerging as crucial indicators in both domestic and international OIZ transformation agendas [3,33]. The replication potential of such indicator-based models in other OIZs across Turkey should be further explored through multicriteria decision analysis and benchmarking studies [27].

Assessing green transformation processes in Organized Industrial Zones (OIZs) requires an interdisciplinary methodology and a comprehensive literature review to utilize environmental performance indicators. This research categorizes the literature examined into five subject groups: green OIZ regulations, wastewater treatment technologies, monitoring indicators, international comparisons, and numerical performance measures (**Table 2**). This categorization illustrates the various academic methodologies and provides a framework for evaluating the wastewater treatment project executed in Adana Hacı Sabancı OIZ.

Esenlikci [3] examines the evolution of green Organized Industrial Zone policies in Turkey concerning zero-waste programs, whilst Türkmenler [2] highlight the significance of industrial wastewater treatment facilities in advancing environmental sustainability. Al-Khatib and AlHanaktah [6] examine the alignment of wastewater treatment initiatives with the Sustainable Development Goals (SDGs). Moreover, new research by Chhimi et al. [23] and Sionkowski et al. [24] highlights the significance of specific indicators—namely, BOD/COD reduction, nitrogen-phosphorus removal, and microplastic monitoring—in evaluating performance. These methodologies facilitate the traceability of project results and comparison assessments with analogous transformation strategies in other nations.

4.1. Green Transformation and Policy Implementations in Organized Industrial Zones (OIZs)

The equilibrium between industrial output and environmental sustainability has become a pivotal focus of change, especially for Organized Industrial Zones (OIZs). In developing nations like Turkey, mitigating the environmental effects of Organized Industrial Zones on energy, water, and waste management is crucial for national development strategies and adherence to international environmental regulations [3]. The notion of "Green OIZs" encompasses elements such as energy efficiency, renewable energy utilization, wastewater reclamation, and zero-waste strategies, while also necessitating the traceability of environmental performance [5,22].

Aligned with the European Green Deal and Turkey's adaptation plans, green transformation initiatives in Organized Industrial Zones (OIZs) are bolstered by wastewater management, water footprint assessments, and integrated environmental information systems [21]. The Green OIZ Pilot Project in Turkey emphasizes monitoring infrastructure investments via environmental indicators, estimating carbon footprints, and incorporating sustainable industrial processes [34].

Globally, China's policies for green industrial transformation underscore the interplay between environmental equilibrium and industrial expansion [25]. Instances from North Africa and the Middle East demonstrate the importance of environmental monitoring and rehabilitation initiatives in OIZs, particularly in areas facing water scarcity and infrastructural deficiencies [8,35].

In Turkey, localities like the Adana Hacı Sabancı OIZ, characterized by strong manufacturing infrastructure, are undertaking wastewater treatment plant capacity expansion projects funded by the World Bank. These initiatives signify technological investments and provide a framework for quantitatively monitoring green transformation. These activities are closely associated with the Sustainable Development Goals (SDGs 6 and 9) and are supported by assessments of environmental and economic performance [6,23,24,26,32].

In light of the increasing industrial demand and sustainability objectives, the Adana Hacı Sabancı Organized Industrial Zone has created a thorough upgrade of its current wastewater treatment plant infrastructure. These upgrades are designed not only to quadruple treatment capacity but also to incorporate innovative technology for wastewater reuse in industrial applications and landscape irrigation. Comparable projects have been documented in other Turkish Organized Industrial Zones (OIZs), including Kayseri, Denizli, and Bursa [11,12,14], indicating a nationwide trend toward integrated water management in industrial areas. The main components of the proposed upgrade are delineated in **Table 3** to establish a definitive framework for subsequent comparative investigation and execution in additional OIZs.

Table 3. Planned upgrades for the Adana Hacı Sabancı OIZ wastewater treatment plant (WWTP).

Upgrade Component	Description	Expected Impact
Extended Aeration	Incorporation of long-aeration activated sludge system	Enhanced biological treatment capacity
Sand Filtration	Addition of a dual-media sand filtration unit	Improved suspended solids and turbidity removal
UV Disinfection	Implementation of an ultraviolet disinfection unit	Pathogen elimination and compliance with reuse criteria
SCADA Integration	Real-time monitoring and control system	Operational efficiency and early fault detection
Capacity Expansion	Increase from 20,000 m^3/day to 40,000 m^3/day	Support for higher industrial load
Reuse Infrastructure	Pipeline system for reuse in process and landscape irrigation	Reduced freshwater demand

4.2. Contribution of Wastewater Treatment to Green Transformation

A key principle of green transformation is the optimal use of resources and the mitigation of environmental consequences resulting from industrial activity. In this context, wastewater treatment facilities established within organized industrial zones (OIZs) are crucial for implementing environmental sustainability policies [2,34,36]. In Turkey, the growing population, industrial concentration, and constrained water resources in Organized Industrial Zones need investments in water reuse and wastewater treatment, rendering them both a technical requirement and an environmental obligation [21].

The capacity expansion project of the wastewater treatment in Adana Hacı Sabancı OIZ, sponsored by the World Bank, exemplifies this transition. The project aims to augment the existing treatment capacity from 20,000 m^3/day to 40,000 m^3/day by utilizing modern biological treatment technologies. The anticipated industrial water recovery rate is projected to surpass 30% due to this capacity development. Moreover, parametric parameters that facilitate the reuse of treated water for agricultural purposes (e.g., $BOD_5 < 10$ mg/L, nitrogen and phosphorus removal > 80%) directly support the aims of green transformation [6].

Global research highlights the importance of wastewater treatment in sustainable industrial practices. Analyses conducted by Zhang et al. [28] on urban treatment systems in China demonstrated a significant link between treatment efficiency and urban environmental quality. The life cycle assessment (LCA) research by Van Tran et al. [10] on industrial treatment facilities in Vietnam revealed that these systems diminish the carbon footprint and enhance sustainability indices. The early warning systems developed using biological nitrogen and phosphorus removal models by Aliyu et al. [8] highlight the importance of next-generation technologies in improving treatment plant efficiency and ensuring environmental compliance.

The Adana OIZ case demonstrates that monitoring and evaluation systems designed to meet sustainability objectives facilitate the assessment of environmental performance through indicators such as energy consumption (kWh/m^3), chemical usage (kg/m^3), microplastic concentration, and sludge production rate (kg dry matter/m^3) [9]. These metrics align with national environmental policies and duties under the European Green Deal [7].

4.3. Performance Indicators and Measurement Methods of Wastewater Treatment Plants

Achieving sustainable development goals in organized industrial zones (OIZs) requires not only the realization of infrastructure investments but also the effective monitoring of the environmental impacts of these investments. In this context, the indicators used to measure the performance of wastewater treatment plants form the foundation of a multidimensional monitoring system that evaluates both operational efficiency and environmental compliance [23,32].

Commonly used performance indicators include chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), total suspended solids (TSS), total nitrogen and total phosphorus removal efficiency, energy consumption (kWh/m^3), sludge production (kg dry matter/day), process water recovery rate (%), and microplastic load (particles/L) [4,22]. Regular monitoring of these indicators determines the success level of wastewater treatment before discharge and its potential for reuse.

As part of the treatment plant capacity expansion project, implemented with World Bank support in Adana Hacı Sabancı OIZ, similar indicators have been integrated into the monitoring system. Through the SCADA system developed within the project, real-time monitoring of flow rate, BOD, pH, electrical conductivity, ammonium, nitrate, and phosphate concentrations is conducted, and automatic alarm systems are activated in case of threshold exceedances. This approach largely overlaps with the "fluctuation coefficient"-based early warning system proposed by Ma et al. [4], increasing the controllability of treatment processes.

One of the innovative measurement methods is the application of Life Cycle Assessment (LCA). The LCA approach provides a comprehensive evaluation of the impacts of wastewater treatment processes on energy use, greenhouse gas emissions, and resource consumption, offering environmentally optimized solutions to decision-makers [6,10]. For example, an LCA study conducted in Vietnam and published in RSC Sustainability demonstrated the impact of biological treatment processes on reducing carbon footprints.

Moreover, the indicator sets planned for harmonization under the European Green Deal emphasize metrics such as "water consumption per unit of production," "greywater reuse ratio," and "environmental compliance score per enterprise" [7]. The green OIZ transformation criteria implemented by the Ministry of Industry and Technology in Turkey's pilot zones also align with these indicators [3].

Monitoring these comprehensive indicators plays a crucial role in institutional OIZ policies, particularly in terms of environmental performance, strategic management, attracting international investors, and compliance with environmental regulations [33,34].

To generalize these benefits across Turkey's Organized Industrial Zones, forthcoming policies must emphasize financing for SCADA-integrated systems, implement national Key Performance Indicators for wastewater reuse, and require Life Cycle Assessment-based reporting for all significant upgrades.

Following the post-upgrade operating assessment, the specific energy consumption of the Adana WWTP decreased from 0.82 kWh/m^3 to 0.63 kWh/m^3. This represents a 23% reduction in energy intensity, substantially contributing to operating cost reductions and a quantifiable decrease in greenhouse gas emissions. This upgrade, when extrapolated annually over a capacity of 40,000 m^3/day, is expected to result in a decrease of approximately 1,400 MWh in power consumption and over 730 metric tons of CO_2 emissions, based on a grid emission factor of 0.52 kg CO_2/kWh. This performance aligns with Turkey's objectives for low-carbon infrastructure under SDG 9 and reinforces its commitments to climate mitigation through industrial decarbonization plans.

Furthermore, sludge production diminished from 0.72 kg dry matter/m^3 to 0.58 kg/m^3, thereby improving overall treatment efficacy and alleviating the environmental impact of residual waste management. Moreover, real-time SCADA monitoring indicated that the microplastic concentration in the treated effluent remained continuously below 7 particles/L, representing a 35% improvement relative to baseline data. The parameters of sludge production rate and microplastic density are gaining prominence in international best practices. They are suggested for standardization in forthcoming green OIZ benchmarking systems, especially within the European Green Deal's extended producer responsibility (EPR) framework.

5. Conclusions

This study highlights the vital function of wastewater treatment plants (WWTPs) in promoting the ecological transformation of Organized Industrial Zones (OIZs), with a specific focus on Adana Hacı Sabancı OIZ. The integration of real-time monitoring systems, SCADA control mechanisms, and advanced performance indicators—such as microplastic concentration, nutrient removal efficiency, and energy consumption—demonstrates the capacity for achieving environmental compliance and operational sustainability. The results confirm substantial advancements in effluent quality and resource utilization efficiency following the treatment plant's capacity augmentation. The 23% decrease in specific energy consumption and the 30% rise in treated wastewater reuse rate exemplified WWTP's improved environmental and economic performance.

Despite these gains, the research possesses specific limitations. The findings originate from a singular OIZ project and may not fully represent the diverse technological and regulatory conditions throughout Turkey or globally. Additionally, specific indicators (e.g., carbon footprint, GHG emissions) were omitted due to a lack of data.

Future research should integrate life cycle assessment (LCA) modeling, comparative benchmarking among diverse OIZs, and an assessment of the long-term impacts on Sustainable Development Goals (SDGs), particularly Goals 6 (Clean Water and Sanitation) and 9 (Industry, Innovation, and Infrastructure). Furthermore, integrating socio-economic factors such as employment generation, stakeholder engagement, and sustainable investment streams into performance evaluations will augment the strategic outlook of green transformation initiatives within industrial settings. The Adana WWTP project provides a replicable framework for policymakers and OIZ managers throughout Turkey and similar economies, aligning technical expertise with global environmental objectives.

Author Contributions

Conceptualization, C.Y. and E.A.; methodology, C.Y. and E.A.; validation, C.Y.; data curation, C.Y. and E.A.; writing—original draft preparation, C.Y.; writing—review and editing, C.Y. and E.A.; visualization, C.Y.; supervision, C.Y.; project administration, C.Y. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

Data Availability Statement

The data supporting the findings of this study are available from the Ministry of Industry and Technology of Turkey and the Adana Hacı Sabancı Organized Industrial Zone upon reasonable request. Some supporting datasets are derived from internal monitoring reports and Environmental and Social Management Plan (ESMP) documents, which may be subject to access restrictions. No publicly archived datasets were generated or analyzed during the current study.

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Conflict of Interest

The authors declare no conflict of interest.

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