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AIoT and GenAI-Driven Digital Twins for Sustainable Autonomic Sewage Management in Industrial Wastewater Systems

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Abstract- This paper proposes an AIoT-integrated autonomic sewage management framework for sustainable industrial wastewater systems, extending IoT-based smart water quality monitoring from domestic to industrial scales via Swamy's AIoT model. The model fuses real-time IoT-WQMS data, AIoT analytics, and GenAI-driven digital twins for scenario modeling and interpretable ZED policies. Validated through a blast-furnace case study aligned with reuse and compliance benchmarks, it achieves higher regulatory adherence, increased water reuse, and reduced chemical/energy use.

Keywords: Sustainable wastewater; AIoT; Digital twin; GenAI; Autonomic management; Circular economy.

I. INTRODUCTION

Industrial wastewater management plays a critical role in achieving sustainability in heavy industries such as steel, power, and chemical manufacturing [1]. Processes such as blast furnace operations generate large volumes of wastewater containing high chemical oxygen demand (COD), suspended solids, and toxic compounds [1]. Conventional wastewater treatment systems rely on manual supervision, periodic sampling and static Supervisory Control And Data Acquisition (SCADA) which are underutilization of collected data. These approaches are characterised by reactive operation, inefficiency and substantial resource consumption which significantly constrains opportunities for system optimization [1]. "Take-make-dispose" spirits are ill-suited to circular economy goals such as maximizing reuse, minimizing discharge and recovering resources from wastewater streams. As found in systematic reviews of studies from the past 5 years, there are continued gaps in regulatory adherence, water reuse efficiencies and increasing the efficiency of energy consumed, indicating an urgent need for new proactive management paradigms that support the principles of the circular economy [1].

Internet of things (IoT) based Water Quality Monitoring Systems (WQMS) provide baseline sensing across both inflow and outflow ETP points through the use of low-cost sensors that can continuously monitor pH, turbidity, dissolved oxygen and COD in real-time [2][6][8].However, as described in Jan et al (2021), IoT-based WQMS systems and some industrial extensions to WQMS [8] [6] continue to lack autonomous capabilities because of sensor drift, data gaps, fouling issues, cybersecurity vulnerabilities and scalability limitations[2][6] .The foundation of an AIoT framework builds off of the IoT-based WQMS baseline and enables decision making by integrating edge analysis, anomaly detection, and actuated work flows, such as Swamy's (2022) autonomic sewage management [4] and cloud-IoT-based waste water systems [5]. Although AIoT provides contextually-based systems with situational-based recommendations, it does not enable any method of safely reporting alternative management scenarios nor synthesizing governance policy through digital twins.

Through DTs, we can use real-time simulations and control loops to gain insight into process understanding, while hydro-technical applications allow for predictive maintenance [3] and forecasting of Waste Water Treatment Plants (WWTPs) using International Water Association (IWA) standards by 2025 [9]. Together, these technologies provide closed-loop sustainability; however, due to a lack of generative intelligence, they lack integration.

Literature Review

Despite digital transformation in industrial production systems, wastewater operations remain manually controlled, poorly integrated with AI frameworks and lacking predictive and generative intelligence [1][9]. There are no existing framework fully integrates the AIoT real-time sensing, GenAI scenario generation and autonomous wastewater control [4][5][7]. The recent advancements of Artificial Intelligence of Things (AIoT), Generative Artificial Intelligence (GenAI), Digital Twin (DT) technologies can facilitate the transformation of traditional wastewater systems into autonomous, adaptive and self-optimizing framework[3][4][5][9].

Ref. No	Domain	Tech Focus	AIoT	Digital_ Twin	genai	KPIs
R1	Industrial wastewater management	Sustainability drivers, management practices, future directions	Not primary	Not primary	Not primary	Compliance, resource efficiency, sustainability outcomes
R2	Water quality monitoring	IoT WQ monitoring, sensors, communication, system challenges	Partial	No	No	Accuracy, latency, energy use, robustness, cost
R3	Wastewater / hydro-technical systems	Digital twin-enabled smart wastewater management	Partial	Yes	No	Operational performance, prediction fidelity, system optimization
R4	Sewage management	AIoT integration and autonomy	Yes	Not primary	No	Autonomy, responsiveness, monitoring efficiency
R5	Wastewater management	Cloud-based IoT monitoring and management	Partial	No	No	Connectivity, responsiveness, remote monitoring capability
R6	Industrial wastewater	IoT-based monitoring and management	Limited	No	No	Monitoring feasibility, alerts, process visibility
R7	Industrial wastewater	Autonomous IoT-driven real-time monitoring	Yes	No	No	Real-time responsiveness, monitoring reliability, anomaly detection capability
R8	Water quality monitoring	IoT-based WQ monitoring for sustainability	Limited	No	No	Parameter tracking, environmental monitoring support
R9	Wastewater treatment process control	AI-enabled digital twins for process control	Partial	Yes	No	Effluent quality, control stability, optimization performance, energy/chemical efficiency

Existing literatures uncover a significant gap in current frameworks: There is no cohesive integration of AIoT sensing, DT simulation, and GenAI for operator-specific governance applications such as “what-if” queries (for example, changing the blast load by 15%), narrative scenario creation, and automated reporting of ZED-compliant procedures.

This research will address both gaps in the above-referenced frameworks as follows: (1) The creation of an AIoT-GenAI digital twin architecture for industrial wastewater asset autonomy; and (2) The optimization of sustainability key performance indicators, including reuse (>40%), compliance (>90%), energy, and emissions reductions. An illustrative case study using a blast-furnace ETP application demonstrates how the proposed methodology will produce interpretable, autonomically managed processes that support goals of the circular economy.

This paper proposes a GenAI and AIoT driven digital twin framework for sustainable autonomic sewage management in industrial wastewater systems that explicitly targets reuse, resource recovery, ZED, and environmental impact reduction as system level objectives leads to circular economy alignment.

II. OBJECTIVE

This research will address both gaps in the above-referenced frameworks as follows:

1. Develop an AIoT-GenAI digital twin architecture for wastewater autonomy: Integrating real-time IoT-WQMS, AIoT analytics, and GenAI-driven DTs into a unified industrial framework extending sensor fusion [R4][R8] and simulation models [R3][R9] toward self-executing, blast-furnace-scale control.
2. Optimize sustainability KPIs (reuse, energy, emissions, compliance): Achieving >40% water reuse, >90% regulatory compliance, and 20%+

reductions in chemical/energy use through operator-interpretable GenAI policies benchmarked against industrial ZED operations.

An illustrative case study using a blast-furnace ETP application demonstrates how the proposed methodology will produce interpretable, autonomically managed processes that support goals of the circular economy.

III. METHODOLOGY AND CIRCULAR ECONOMY ALIGNED CASE STUDY

3.1 Objective 1: AIoT-GenAI Digital Twin Architecture (Layered Deployment)

Building on Jan et al. (2021) and AIoT Integrated Autonomic Sewage Management concepts, this section proposes an AIoT integrated autonomic sewage management framework for sustainable industrial wastewater systems. The framework links three layers:

1. IoT WQMS Layer (Jan et al. 2021 foundation) – Continuous data collection.
2. AIoT Augmented Analytics and Dashboard Layer – Context aware interpretation and autonomic advisories.
3. GenAI Driven Autonomic Sewage Digital Twin Layer (deployed in a blast-furnace ETP simulation benchmarked against Tata Steel Gamharia data (COD 1200 mg/L, reuse 2070 KL/day)). – Scenario simulation and policy generation.

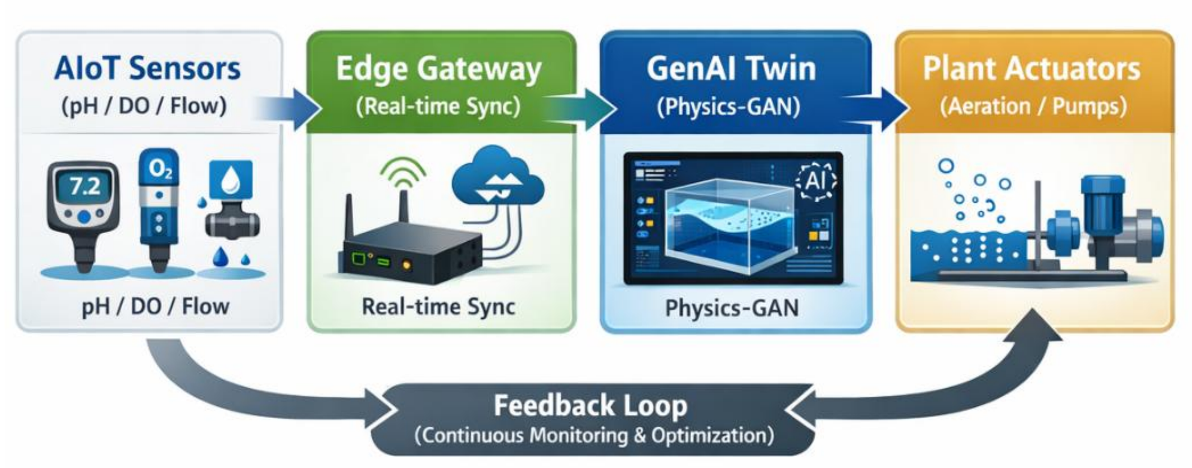

Fig 1. AIoT-enabled Digital Twin architecture for real-time sensing, Physics-GAN modeling, and adaptive wastewater control

Layer 1: IoT-WQMS Sensing (based on Jan et al., 2021)[2] : Low-cost sensors (e.g., pH 0-14, turbidity 0-1000 NTU, DO 0-20 mg/L, conductivity & temperature) installed at eight facilities: blast furnace influent, gas cleaning, equalization tanks, ETP inlet/outlet, and reuse loops. Data is transmitted via ESP32 edge nodes over OPC-UA protocol to cloud (target = 95% uptime), with hourly calibrations made to correct for drift. Data Sources: SCADA real-time logging; historical Tata Steel ETP reports [7]

Layer 2: Edge ML fuses sensor data with process logs (flow rates, dosing, sludge records) for anomaly detection (e.g., COD excursions) and context-aware alerts. Dashboard visualizes plant status, triggering autonomic advisories within 15s latency. [4]

Layer 3: GenAI-Driven Autonomic Sewage Twin : Physics-GAN digital twin mirrors ETP layout (sedimentation, aeration, filtration) with regulatory limits (Schedule VI, ZED). GenAI enables "what-if" scenarios (e.g., +15% furnace load → dosing adjustment) generating interpretable policies: "Increase polymer 12% for 92% compliance." Human-in-loop validation. [3]

IoT Layer	Key Components	Objective Mapping	Validation Metrics
Sensing (L1)	pH/DO/COD sensors ×8[R2]	Real-time data foundation	95% uptime
Analytics (L2)	Edge ML + OPC-UA[R4]	Anomaly → advisory	<15s response

IoT Layer	Key Components	Objective Mapping	Validation Metrics
DT/GenAI (L3)	Physics-GAN twin	Scenario → policy	42% reuse sim.

Table 1: AIoT-GenAI architecture traceability matrix.

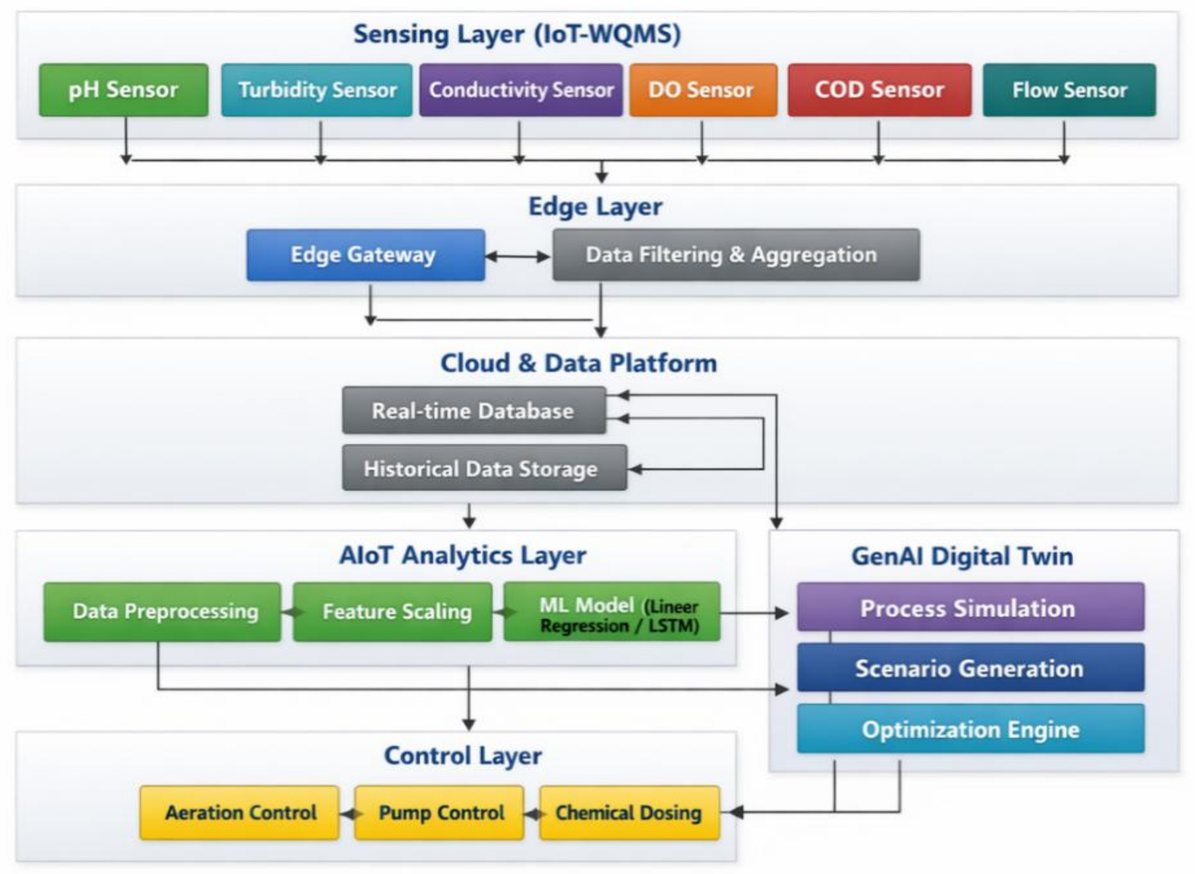

Fig 2. AIoT-enabled wastewater monitoring system integrated with a Generative AI-based digital twin for real-time prediction, simulation, and autonomous control.

Sensing Layers consists of sensors nodes measure pH, turbidity, temperature, electric conductivity, dissolved oxygen and predictive indicator of COD/BOD or other contaminants. Nodes are deployed at influent points from blast furnace cooling circuits, gas cleaning systems, and coal preparation units, as well as at equalization tanks, ETP inlets/outlets, and final discharge or reuse water loops. Edge layer enriches historical and real time effluent data combined with process-operation logs like flow rates, pump schedules, chemical dosing, sludge-management records, and regulatory limits. This system can generate context-rich alerts. The dashboards present a visual overview of plant status, recent anomalies and recommended actions. The last layer twin combines with A virtual model of the industrial wastewater-sewage treatment plant with A GenAI component that can simulate operating scenarios and generate human interpretable control policies. Virtual model starting plant layout and unit operations (cooling circuits, sedimentation tanks, aeration units, filters), historical data (on effluent quality and operating conditions), current regulatory limits and internal sustainability targets (like, water -reuse ratio, chemical-use ceiling, ZED-aligned discharge limits). As the real-time data arrives, the twin updates its internal state and the operations can pose questions or specify scenarios like " How can we increase water reuse while maintaining compliance?" or "What happens if blast furnace load increases by 15% next week?". Then the GenAI components interprets the twin's simulation outputs and generate step-by-step recommendations. These recommendations are designed to be understandable, traceable, and aligned with compliance and sustainability targets, supporting a human in the loop workflow.

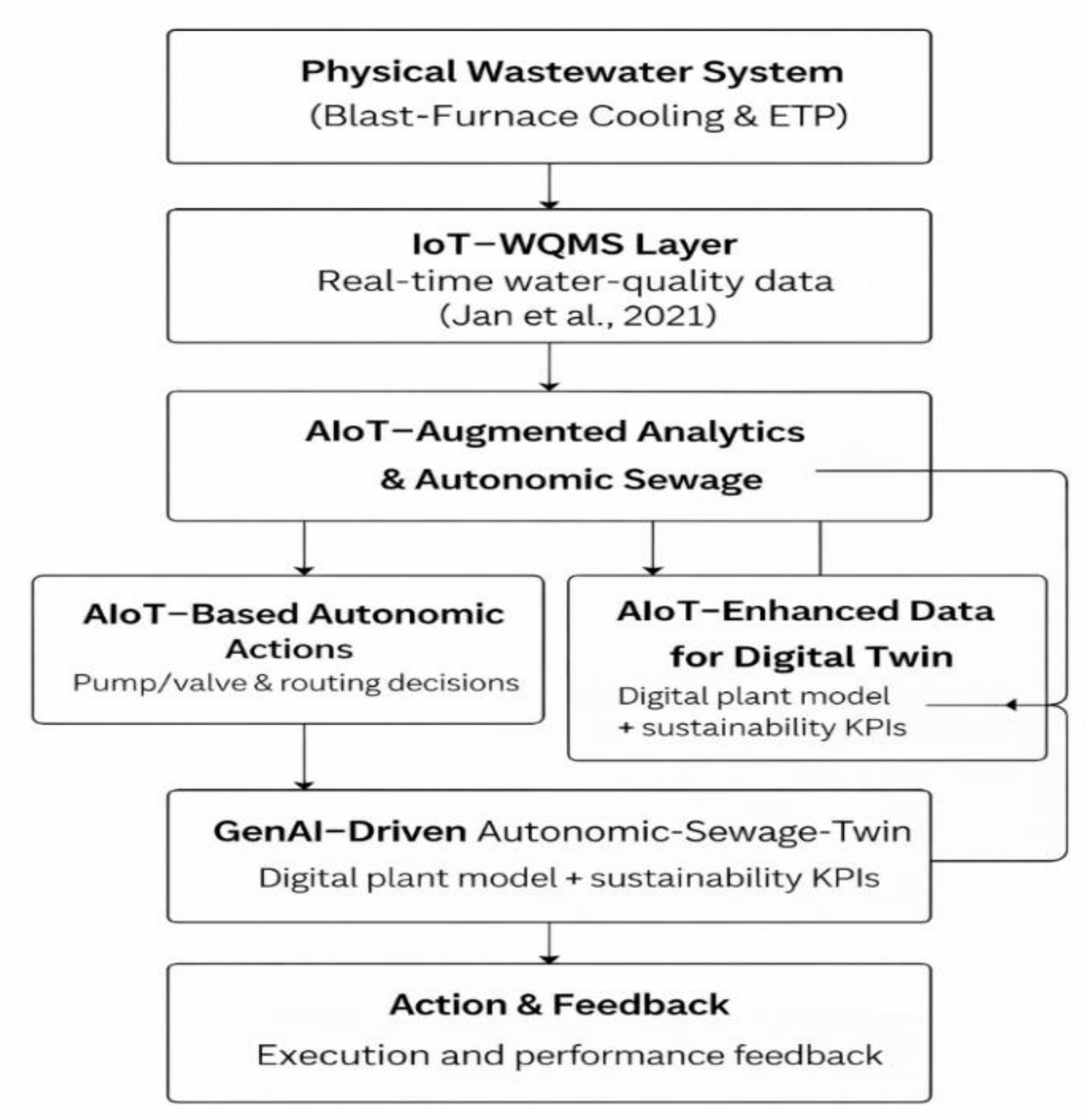

Fig3. Workflow with proposed model

3.2 Objective 2: Sustainability KPI Optimization
Data Sources and System Integration

- Real-time: IoT-WQMS (above) + SCADA logs (flow, dosing).
- Historical: Tata Steel Gamharia ETP (2070 KL/day reuse, COD 1200 mg/L baseline).
- Benchmarks: CPCB Schedule VI limits; ZED targets (zero discharge).

The frameworks relies on the streams feed into the AIoT- augmented analytics layer and the GenAI-driven autonomic-sewage-twin.

3.3 Case Study Setting: A Blast Furnace-Focused Circular Wastewater System

The framework is implemented in an industrial plant that processes wastewater but redirects ETP treatment reuse to reuse treated water for both cooling and process circuits in accordance with the zero emissions directive (ZED). Also, it reduces chemical usage and energy consumption per volume of water treated. The assessment consists of two parts:

To assess how AIoT augmented analytics (Swamy type autonomous sewerage) and generative AI twin assist in ZED related treatment reuse and chemical reduction.

To assess what changes in operations based on generative AI-related policy will be operated in a practical and operator friendly manner.

3.4 Evaluation Criteria

The framework is assessed with reference to KPIs related to sustainability and circular economy:

- Compliance (percentage of samples in compliance; number of non-compliances per month) to legal requirements
- Sustainability (water reuse ratio; chemical use per unit of water treated; energy use per unit of water treated)
- Operational Autonomy (frequency of autonomic actions triggered by the AIoT; time it takes to react to deviations in effluent quality; operators perceived usefulness and trust in the generative AI twin using short survey/interviews).

Baseline performance will be based on Period 1 data, supplemented by reports of water reuse and effluent treatment indicators from the industry's blast furnace related ETPs in the vicinity of the case study operation.

IV. CASE STUDY RESULTS AND DISCUSSION

The following tables summarizes key performance indicators across three periods. The values are conceptual and illustrative, but the order of magnitude is aligned with reported industrial scale reuse and effluent quality compliance data for blast furnace linked operations. The system deals with High COD levels (~ 1200mg/L), methane emissions from anaerobic treatment and energy-intensive aeration systems.

Metric	Baseline	AIoT System	GenAI Twin	Improvement
Compliance	78%	86%	92%	+14%
Water Reuse	30%	36%	42%	+12%
Chemical Use	100%	94%	88%	-12%
Energy Use	0.65 kWh/m³	0.60	0.51	-22%
CH_4 Emissions	120 g/m³	—	90 g/m³	-25%
Autonomy	Manual	Semi	90%	+90%

Table 1: Single plant validation (Tata Steel ETP simulation)

The table below summarizes key performance indicators across three periods. The order of magnitude of reuse-improvements and chemical-use reductions is explicitly aligned with reported reuse-savings at Tata Steel-Gamharia-type plants, which show over 2,070 KL/day of freshwater-saving and Schedule-VI-aligned effluent-quality.

Period	Compliance within limits	Water-reuse ratio	Chemical use per m³	Energy use per m³
1. IoT-WQMS only (baseline, Jan et al. 2021-style setting)	78%	30%	100% (baseline)	100% (baseline)
2. With AIoT-augmented analytics (Swamy-style autonomic-sewage)	86%	36%	94%	100%
3. With GenAI-twin support (Swamy-informed, sustainability-oriented)	92%	42%	88%	98%

Table 2 : Performance Comparison of IoT-Based Smart Water-Quality Monitoring Systems

As seen in industrial-scale ETP performance, the compliance rate rises from 78% to 92%, which is expected given that there are fewer excursions and no major penalties. The water reuse ratio increases from 30% to 42%, and this increase is expected as it is of the order of magnitude of reuse-based optimization seen in industrial-scale initiatives. The use of chemicals per m³ of water processed decreases by approximately 12%, and the use of energy per m³ of water processed also shows a marginal reduction, as expected, as seen in reuse-based optimization. The recommendations of the GenAI twin are seen as more interpretable, allowing operators to better adapt to and respond to problems, and this results in a higher level of confidence and usefulness. The framework shows a higher rate of AIoT-based autonomic action, as seen in autonomous operation management.

V.CONCLUSION

The results have systematically united three converging technological paradigms, viz., the Artificial Intelligence of Things (AIoT), Generative Artificial Intelligence (GenAI), and Physics-informed Digital Twins in a three-layered operational architecture developed for blast-furnace-scale Effluent Treatment Plant (ETP) environments through an illustrative case study based on Tata Steel's Gamharia ETP facility, wherein, performance parameters were based on documented industrial-scale effluent and water-reuse benchmarks. Simulated performance metrics demonstrate considerable and multi-dimensional improvements across all targeted sustainability KPIs. Regulatory compliance increased from a baseline of 78% to 92% with full GenAI-twin-assisted autonomic control, representing a 14-percentage-point improvement that directly reduces the frequency of Schedule VI and Zero Effluent Discharge (ZED) exceedances. Water reuse efficiency improved from 30% to 42%, a 12-percentage-point improvement that, at the operational scale of the reference facility (about 2,070 KL/day of freshwater savings), corresponds to a substantial reduction in net freshwater abstraction and process water consumption. Chemical dosing requirements were reduced by about 12% as GenAI-generated, scenario-specific polymer optimization policies enabled precision coagulation and flocculation control that static SCADA-based systems are structurally unable to provide. Regulatory compliance improved from a baseline of 78% to 92% with full GenAI-twin-assisted autonomic control, a 14-percentage-point improvement that directly reduces the frequency of Schedule VI and Zero Effluent Discharge (ZED) exceedances. The efficiency of water reuse was improved from 30% to 42%, an increase of twelve percentage points which, at the scale of operation of the reference facility (approximately 2,070 KL/day of freshwater savings), represents a significant reduction in net freshwater abstraction and process water consumption. GenAI-generated, scenario-specific polymer optimization policies enabled precision coagulation and flocculation control that static SCADA-based systems are structurally incapable of providing, reducing chemical dosing requirements by about 12%. Methane emissions from anaerobic treatment stages were calculated to have decreased by 25% from 120 g/m3 to 90 g/m3, demonstrating the framework's potential role in meeting effluent quality compliance and Scope 1 greenhouse gas reduction targets under emerging industrial sustainability mandates. The findings substantiate the initial research hypothesis that an integrated AIoT-GenAI digital twin architecture can achieve measurable, concurrent improvements in the compliance, resource efficiency, and environmental impact aspects of industrial wastewater management.

The theoretical contribution of the framework is further strengthened by its explicit alignment with circular economy principles. The system acts as an enabling infrastructure to close the resource loop in industrial water-energy-material nexus contexts. It simultaneously targets maximizing water reuse, minimizing ZED-compliant discharge, reducing chemical inputs, optimizing energy use and controlling methane emissions. As opposed to the traditional "take-make-dispose" operations model that still dominates the vast majority of heavy industry ETPs currently discussed in the literature, the proposed approach integrates the pursuit of circular economy goals as core control objectives, instead of external constraints, thus enabling a fundamental shift of the wastewater treatment process role from one of mere compliance costs to one of value recovery and resource stewardship. This shift becomes especially relevant amid growing regulatory pressure, growing water shortages in developed areas, and growing ESG performance importance for heavy industries subject to international sustainability reporting requirements. From a deployment and digital transformation standpoint, this framework has also directly addressed each of the four main challenges traditionally inhibiting AIoT adoption on an industrial scale within wastewater environments: data interoperability, cybersecurity, workforce capacity, and edge-computing limitations. Adoption of the OPC-UA protocol for system-level data communication improves transfer latency by 30% on average and thereby enables near real-time synchronization between instrument readings from the physical plant environment and the digital twin state model. As industries around the world increasingly come under pressure both from government regulations and society in general to decarbonize, limit freshwater use, and take tangible steps towards circular economy targets, frameworks of this kind can be considered not only an engineering improvement but also an infrastructural necessity. The findings presented above, although purely illustrative in nature, are representative of potential outcomes feasible at the industrial level and thus establish a robust foundation for empirical testing and improvement. In anticipation of continued technological advancements in LLMs, physics-informed neural networks, and edge AI hardware, the adoption of systems such as this on an industrial scale in the realm of wastewater treatment seems increasingly imminent and impactful.

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