ATP-Based Microbial Control for Precise Wastewater Treatment

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The overuse of non-oxidizing biocides in industrial wastewater purification systems can result in excessive chemical costs without proportional improvements in microbial control. This study addresses the lack of scientific control over biocide dosage at the Industrial Wastewater Purification Plant (IWWPP) of China Steel Corporation, where non-oxidizing biocides are routinely added based on vendor recommendations. This study hypothesizes that real-time microbial ATP monitoring can provide a scientific basis for optimizing biocide usage without compromising membrane protection. The study monitored adenosine triphosphate (ATP) concentrations at five key points in the water purification process before and after reductions in biocide dosing. The results showed that baseline ATP values at all points, except for raw influent, were below 10 pg/mL, indicating extremely low microbial load and potential biocide overuse. Two-stage biocide reduction trials were performed: (1) biocide shutdown at upstream dosing points, and (2) further biocide reduction at the reverse osmosis (RO) inlet. Microbial ATP concentrations increased during both trials but remained below the 100 pg/mL intervention threshold. Importantly, no significant shortening of filter replacement cycles or RO membrane cleaning frequency was observed. The study concludes that microbial ATP monitoring is a valid method for evaluating and adjusting biocide dosing, achieving a 55% cost reduction with negligible operational impact. These findings demonstrate the feasibility of implementing ATP-based microbial monitoring for biocide control in industrial membrane systems.

Keyword: Microbiological monitoring, ATP, Biocide optimization, Wastewater purification

1. INTRODUCTION

Industrial wastewater treatment facilities play a vital role in ensuring that effluents discharged into the environment meet regulatory and environmental standards. These facilities employ a combination of physical, chemical, and biological treatment processes to remove contaminants from industrial effluent. Among the many challenges faced in these operations, microbial fouling—particularly in membrane-based systems such as ultrafiltration (UF) and reverse osmosis (RO)—remains a significant operational concern. Biofilm formation on membrane surfaces can result in increased energy consumption, reduced water flux, elevated transmembrane pressure, and eventually membrane degradation or failure.

To address this issue, many industrial facilities, including the IWWPP of China Steel Corporation, utilize non-oxidizing biocides as part of their standard water treatment protocols. These biocides are designed to inhibit microbial proliferation by disrupting essential cellular functions. However, in practice, dosing regimens are frequently based on conservative vendor recommendations or historical practices rather than on real-time microbial activity data. This often leads to either underdosing—posing a risk of microbial breakthrough and fouling—or overdosing, which results in excessive chemical consumption and potential environmental risks.

In recent years, the use of adenosine triphosphate (ATP) as a rapid indicator of microbial activity has gained attention in the field of water quality management. ATP is a universal energy carrier molecule found in all living cells. Its presence and concentration serve as a reliable surrogate for microbial biomass. Utilizing bioluminescence-based ATP assays, operators can detect ATP levels within minutes, enabling more responsive and informed decision-making regarding microbial control. Although ATP monitoring has been widely applied in drinking water systems and various industrial water applications, its utility for precise biocide dosage optimization in complex industrial wastewater contexts—especially those involving unique chemical and biological interactions in facilities like the IWWPP—has not yet been extensively validated.

This study proposes a novel application of microbial ATP monitoring in optimizing biocide dosing within an industrial wastewater treatment setting. The primary hypothesis is that ATP levels, when monitored at strategic points along the treatment process, can serve as effective indicators for evaluating the sufficiency of microbial control and guiding biocide dosing decisions. This approach represents a shift from fixed-rate dosing to a responsive, condition-based strategy. By correlating ATP data with operational metrics such as RO membrane differential pressure, filter replacement intervals, and cleaning frequency, the study aims to establish a scientific basis for improving both the efficiency and cost-effectiveness of disinfection practices.

Furthermore, this study seeks to bridge the gap between microbial monitoring technologies and plant-level operational practices. By integrating ATP-based assessments with existing water treatment protocols, the goal is to develop a practical framework that can be adopted by operators to enhance performance while minimizing chemical use. The broader implications of this approach extend beyond economic savings, including the potential for reducing environmental footprint and improving the sustainability of water treatment operations. Ultimately, this research provides empirical evidence and operational insight that supports the adoption of microbial ATP monitoring as a core component of industrial water treatment management.

2. EXPERIMENTAL METHOD

2.1. ATP Sampling and Monitoring Protocol

To evaluate microbial activity throughout the treatment process at the Industrial Wastewater Purification Plant (IWWPP), ATP monitoring was implemented at five strategic sampling locations along the water purification line: (1) ultrafiltration (UF) inlet, (2) UF permeate, (3) UF tank outlet, (4) post-cartridge filter, and (5) reverse osmosis (RO) inlet. These sampling points were selected to represent distinct stages in the treatment sequence, allowing for a comprehensive assessment of microbial load dynamics across the system.

ATP concentrations were measured using a commercial bioluminescence assay kit (Quench-Gone Aqueous, LuminUltra) and a PhotonMaster™ luminometer. The assay is based on the luciferin–luciferase reaction, in which ATP serves as a substrate and emits light proportional to its concentration. The resulting luminescence is quantified in relative light units (RLU), providing a rapid indication of microbial biomass.

To facilitate interpretation, ATP results were categorized into three microbial risk levels based on industry benchmarks and the kit manufacturer's guidelines. ATP concentrations below 10 pg/mL were classified as excellent, indicating minimal microbial presence. Values between 10 and 100 pg/mL were designated as alert, suggesting elevated microbial activity that warrants observation. Readings exceeding 100 pg/mL signaled a need for immediate intervention.

2.2. ATP Extraction and Quantification Procedure

ATP extraction and quantification were performed in accordance with the QGA kit protocol. Water samples (50 mL) were drawn into sterile containers and immediately processed. Each sample was filtered through a membrane using a sterile syringe to retain microbial cells on the filter surface. The filter was rinsed with LumiClean solution to remove interfering substances and air-dried using a 60 mL syringe to eliminate residual moisture.

To extract intracellular ATP, 1 mL of UltraLyse 7 reagent was slowly pushed through the filter. The lysate was collected into a 9 mL UltraLute dilution tube and gently inverted to ensure uniform mixing. For quantification, 100 μL of rehydrated Luminase enzyme was dispensed into a clean assay tube to establish background luminescence. Subsequently, 100 μL of the lysate was added to the tube, which was then gently mixed and placed immediately into the luminometer for RLU measurement within 10 seconds.

All reagents were brought to room temperature before use. Final ATP concentrations (pg/mL) were calculated using a calibration curve generated with UltraCheck ATP standards and processed using LumiCalc™ software provided by the manufacturer.

2.3. Biocide Application Strategy and Test Phases

The biocide application system consisted of three metering pumps dosing non-oxidizing biocide at designated points along the treatment train: upstream of the UF tank, after the UF tank, and just before the RO feed. These points were chosen to provide comprehensive microbial control throughout both the UF and RO systems. Under normal conditions, biocide was continuously added based on estimated flow rates, as flowmeters were not installed at all injection points.

To evaluate the feasibility of reducing biocide usage based on microbial data, the study was structured into three operational phases. The baseline phase reflected existing vendor-recommended dosing rates. In Test Period 1, biocide dosing was suspended at both UF injection points while continuing at the RO inlet. In Test Period 2, the dosage at the RO inlet was reduced from 7.83 ppm to 4.7 ppm while upstream dosing remained off. Each phase spanned a period ranging from 50 to 100 days to allow for stabilization and observation of microbial responses and operational changes.

2.4. Operational Performance Indicators

Operational data were collected in parallel with ATP measurements to evaluate system performance under varying biocide regimes. The system employed a two-stage reverse osmosis (RO) configuration, and membrane differential pressures were independently recorded for Stage 1 and Stage 2 to assess potential fouling behavior in each segment. Key performance indicators also included cleaning-in-place (CIP) frequency and cartridge filter replacement intervals. Increases in membrane differential pressure can signal biofouling or clogging, while shorter filter replacement cycles and more frequent CIP procedures often reflect deteriorating water quality or microbial contamination.

Data from these operational indicators were correlated with ATP trends to identify whether microbial load influenced performance and to determine the threshold at which microbial presence might begin to compromise system stability.

2.5. Biocide Consumption Data Collection

Biocide usage data were recorded daily at each dosing location using existing chemical inventory logs and operator input records. The price per kilogram of the biocide was fixed at NT$27 throughout the study. These data were aggregated into monthly summaries and aligned with each operational phase to support later evaluation of dosing efficiency and economic outcomes.

3. RESULTS AND DISCUSSION

To contextualize the monitoring results and dosing strategy, the overall process layout of the Industrial Wastewater Purification Plant (IWWPP) at CSC is illustrated in Figure 1. This schematic depicts the sequential treatment stages and highlights the three biocide injection points—upstream of the UF tank, downstream of the UF tank, and at the RO feed. It also marks the five sampling locations where microbial ATP levels were tracked. This visual reference provides a comprehensive overview of the system's flow path and facilitates understanding of how ATP levels evolved in relation to biocide adjustments across the treatment process.

3.1 ATP Assay Reflects Microbial Activity Across Treatment Stages

ATP measurements were conducted at five key points along the water purification process: the UF inlet, UF permeate, UF tank outlet, post-cartridge filter, and RO inlet. Under baseline conditions, all ATP concentrations except at the UF inlet were below 10 pg/mL (Table 1), indicating low microbial load in most parts of the system. The UF inlet showed an average of 171.8 pg/mL, as expected from untreated industrial wastewater. This suggested that the existing biocide dosing was likely more than sufficient and possibly excessive for the downstream sections, which had consistently low microbial ATP concentrations.

Upon suspending biocide dosing at the UF-related injection points (Test Period 1), the average ATP levels in downstream sections rose slightly but remained under 100 pg/mL. The UF tank outlet increased to 15.9 pg/mL and the RO inlet to 12.7 pg/mL (Table 2). These were still within the "Level 2 - Alert" range and did not trigger

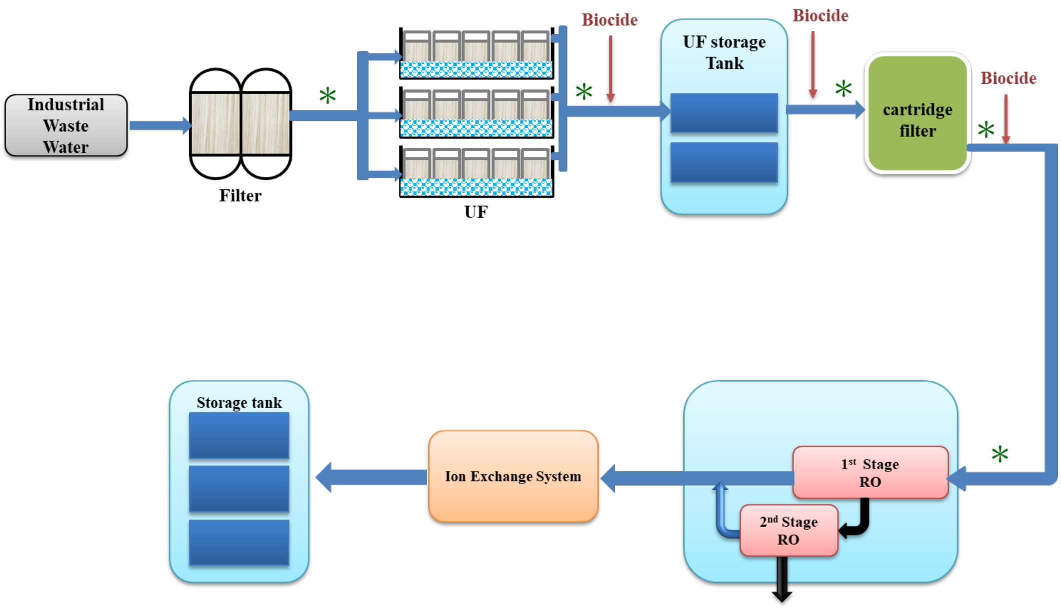

Fig.1. IWWPP Biocide Injection and ATP Sampling Points Schematic (*indicates sampling point for ATP testing).

Table 1 Baseline ATP Concentrations at Key Sampling Points in the Industrial Wastewater Purification Plant (IWWPP).

pg/mL	UF inlet	UF permeate	UF tank outlet	post-cartridge filter	RO inlet
Max.	337.3	6.2	6.6	9.1	9.4
Min.	73.8	0.3	3.8	6.2	1.9
Mean	171.8	2.8	5.3	7.3	5.5
SD	144.1	3.1	1.4	1.6	3.8

Table 2 Average ATP Concentrations at Key Sampling Points During Test Period 1 (Upstream Biocide Dosing Suspended).

pg/mL	UF inlet	UF permeate	UF tank outlet	post-cartridge filter	RO inlet
Max.	457.6	22.9	62.6	13.9	35.6
Min.	67.6	0.5	2.3	1.8	3.1
Mean	253.3	5.3	15.9	6.3	12.7
SD	141.5	7.0	18.9	4.0	9.1

the intervention threshold. The observed increases were considered acceptable, providing a safety buffer for microbial activity. This indicated that a portion of the biocide dosing at the UF stage may not be necessary under current water quality conditions.

When the RO inlet biocide dose was further reduced from 7.83 ppm to 4.7 ppm (Test Period 2), ATP at the RO inlet rose to 18.0 pg/mL (Table 3). Although this represented a measurable increase, the microbial activity remained within a manageable range. These results confirmed that microbial ATP levels could serve as a responsive and sensitive indicator to guide adjustments in biocide dosing. The ability to detect subtle changes in microbial load in near real-time offers a valuable operational advantage, supporting a shift toward precision biocide management rather than routine overdosing.

3.2 Operational Stability Maintained During Biocide Reductions

Operational parameters, including RO Stage 1 differential pressure, CIP frequency, and filter replacement intervals, were monitored throughout the study to assess whether reduced biocide usage impacted overall system performance. In Test Period 1, Stage 1 differential pressure increased slightly from 1.36 to 1.49 kg/cm², and Stage 2 differential pressure also showed a slight increase from 0.81 to 0.88 kg/cm² (Table 4). This change remained within normal operating limits and did not raise immediate concern. Cartridge filters continued to be replaced every 48 days (Table 5), which matched the baseline replacement cycle. Only one membrane CIP event occurred during the test period, consistent with the frequency under full biocide dosing conditions.

In Test Period 2, although ATP values further increased due to additional biocide reduction at the RO inlet, no deterioration in system performance was observed. RO differential pressure held steady at an average of 1.47 kg/cm² over the 106 days, and Stage 2 differential pressure remained steady at 0.88 kg/cm² (Table 4). Two CIP events were recorded, a slight increase from the previous phase, but not significant enough to suggest accelerated fouling or microbial accumulation. Surprisingly, cartridge filter lifespan increased to an average of 78 days (Table 5), possibly due to reduced chemical-induced interference or residual effects on particle transport.

These observations validated that ATP levels under 100 pg/mL could be tolerated in the system without causing operational instability. The consistency of RO pressure and filter replacement frequency indicates that microbial regrowth remained under control even with reduced chemical input. This finding reinforces ATP's practical utility as a decision-making tool that balances the trade-off between biocide efficacy and chemical economy. Furthermore, it highlights the resilience and buffer capacity of the existing membrane system under optimized microbial control conditions.

Table 3 Average ATP Concentrations at Key Sampling Points During Test Period 2 (Further RO Inlet Biocide Reduction).

pg/mL	UF inlet	UF permeate	UF tank outlet	post-cartridge filter	RO inlet
Max.	623.8	34.8	61.7	26.3	55.6
Min.	107.6	1.4	2.6	2.7	3.4
Mean	237.6	9.6	22.4	12.6	18.0
SD	148.0	8.5	18.4	8.7	15.2

Table 4 Operational Performance Indicators of the RO System Across Baseline, Test Period 1, and Test Period 2.

	Baseline	Test Period 1	Test Period 2
Stage 1 ΔP (kg/cm2)	1.36	1.49	1.47
Stage 2 ΔP (kg/cm2)	0.81	0.88	0.88
Total Duration (days)	96	50	106
Number of CIPs	1	1	2

Table 5 Cartridge Filter Replacement Intervals Across Baseline, Test Period 1, and Test Period 2.

	Baseline	Test Periods 1 and 2
Number of Filter Replacements	7	2
Total Duration (days)	324	156
Replacement Interval (Days)	46	78

3.3 Cost Reduction Achieved Through ATP-Guided Dosing

Before any intervention, the facility consumed an average of 2,556 kg of non-oxidizing biocide per month, at a unit cost of NT$27/kg. This corresponded to a recurring monthly chemical expenditure of NT$69,010. Following the staged reduction approach guided by microbial ATP monitoring, average monthly consumption fell to 1,138 kg. This represented a 55% reduction in chemical usage and translated to savings of approximately NT$370,000 on an annual basis.

The magnitude of cost savings demonstrates the financial potential of transitioning from fixed, supplier-recommended dosing schemes to an evidence-based, condition-responsive strategy. Notably, these savings were achieved without any observed penalties in system performance, membrane longevity, or microbial breakthrough. The ATP assay, costing only a fraction of the chemical savings, provided a valuable feedback loop for making rational dosing decisions.

This cost-benefit outcome underscores the broader value of microbial monitoring in process optimization. In addition to immediate financial gains, reduced chemical use lowers the environmental impact associated with biocide discharge and potentially extends the lifespan of treatment components exposed to aggressive chemical agents. The study supports the incorporation of ATP-based decision tools not only for improved microbiological control but also as part of a cost-conscious, sustainable operation strategy.

3.4 Implications for Long-Term Control Strategy

Although short-term results indicated that reducing biocide dosage did not affect system stability, it is important to recognize the potential for cumulative effects over longer time frames. Microbial regrowth, biofilm maturation, and slow-fouling phenomena may take weeks or months to manifest, particularly in membrane systems where fouling occurs gradually and may not be detected until performance degrades noticeably. Therefore, the integration of ATP monitoring into routine practice is essential for maintaining early warning capacity.

The study suggests establishing a facility-specific baseline for acceptable ATP levels, with a proposed operational threshold of maintaining RO inlet ATP under 50 pg/mL for long-term stability. This level provides a conservative margin below the intervention trigger while allowing some operational flexibility. Compared to conventional plate count methods, ATP monitoring offers significant advantages in speed, sensitivity, and operational relevance. Traditional culture-based methods often require 24–48 hours to yield results and only reflect the culturable fraction of the microbial population, which can significantly underestimate actual bioactivity. In contrast, ATP assays capture the total microbial biomass, including viable but non-culturable cells, and produce results within minutes. This makes ATP a more practical and informative tool for real-time process monitoring in membrane systems such as the IWWPP.

In the future, incorporating online ATP sensing technology or linking ATP results to automated dosing control could enable fully closed-loop biocide management. This would further reduce the need for manual testing and subjectivity in decision-making. In summary, microbial ATP monitoring proved to be an effective tool for detecting biocide overuse and guiding confident dosing reductions. When combined with conventional operational indicators, it offers a practical, rapid, and quantitative method to sustain membrane integrity, optimize chemical usage, and support long-term process efficiency in industrial wastewater treatment.

4. CONCLUSION

This study validated the use of microbial ATP monitoring as an effective tool for optimizing non-oxidizing biocide dosing in membrane-based industrial wastewater purification systems. By strategically implementing ATP assays at five critical locations throughout the treatment process, the research established a clear link between microbial activity and system performance. The results demonstrated that biocide dosing at the CSC IWWPP had been more aggressive than necessary, as baseline ATP concentrations in most downstream sections remained well below the 100 pg/mL intervention threshold.

Guided by real-time microbial data, a two-phase biocide reduction strategy was successfully implemented. The first phase involved suspending upstream biocide injection, while the second phase reduced biocide dosage at the RO inlet. In both cases, microbial ATP levels increased moderately but remained within acceptable ranges, never exceeding the alert threshold. More importantly, key performance indicators—including RO differential pressure, CIP frequency, and cartridge filter replacement intervals—showed no signs of deterioration. This confirmed that microbial regrowth remained under control despite reduced chemical input.

Economically, the study achieved a 55% reduction in biocide consumption, resulting in an estimated annual cost savings of NT$370,000. These savings were realized with ATP testing kits and without compromising system stability or membrane integrity. The results underscore the value of transitioning from vendor-driven fixed dosing schemes to a data-driven, condition-responsive strategy enabled by ATP monitoring.

Furthermore, the rapid turnaround and sensitivity of ATP assays—capable of detecting total microbial biomass, including viable but non-culturable organisms—highlight their superiority over traditional culture-based methods for real-time process control. As a result, ATP monitoring offers a practical and scalable solution for early detection of microbial resurgence in membrane systems.

Looking ahead, the integration of ATP monitoring into routine operations—and potentially into automated dosing control systems—holds promise for further enhancing process sustainability, chemical efficiency, and long-term system reliability. Overall, this study demonstrates that ATP-guided microbial control is a feasible, effective, and environmentally responsible approach for managing biofouling risks in advanced wastewater reuse systems.

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