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# Automated Real-Time Smart Dose Control for Disinfection: Digital Twin Implementation based on Integral Contact Time

E. Jang*, S. Mitobe**, E. Cornfoot*, K. Manoli**, J. Walton*, D. Santoro*

* USP Technologies Canada, 3020 Gore Road, London, Ontario N5V 4T7 Canada, ejang@usptechnologies.com

** Lambton College, 1457 London Rd, Sarnia, Ontario N7S 6K4 Canada, sierra.mitobe@lambtoncollege.ca

**Abstract**

This study develops a digital twin framework for real-time automated smart dose control in wastewater disinfection, leveraging the Integral Contact Time (ICT) metric to improve chemical usage efficiency over conventional flow-pacing systems. Traditional flow-pacing methods adjust disinfectant dosing solely based on flow rates, disregarding water quality variations, often leading to chemical overuse and ineffective disinfection. The ICT-based approach continuously monitors residual disinfectant at the disinfection basin's influent and effluent, dynamically adjusting dosing by calculating real-time initial demand and decay rates, ensuring precise disinfectant application to optimize disinfection efficacy while minimizing chemical consumption. Validation using a lab-scale batch pilot system demonstrated effective disinfection performance, with key components including dynamic dose adjustment via real-time calculations, continuous disinfectant residual monitoring to maintain effective disinfection, and a digital twin simulation platform for predictive insights. The monitoring results show the system's adaptability to varying water quality and operational conditions, ensuring efficient and sustainable disinfection while validating ICT calculation methods for maintaining disinfection standards and target ICT levels under variable conditions. These findings lay a foundation for integrating the ICT-based framework into digital twin models for wastewater treatment. Future work will focus on scaling up the side-stream pilot system for full-scale applications, incorporating contact basin hydraulics, and refining process optimization through enhanced digital twin integration. This research underscores the transformative potential of ICT-based digital twin technology in wastewater treatment, enhancing operational efficiency and sustainability.

**Keywords**: Integral contact time; Smart dosing control; Sustainability; Wastewater disinfection

## Introduction

Wastewater effluent disinfection is critical for safeguarding public health and environmental safety. Conventional flow-pacing dosing methods often fail to account for water quality variability, leading to inefficient chemical usage and challenges in meeting microbial reduction targets. This study introduces a digital twin framework employing the Integral Contact Time (ICT) metric to optimize real-time disinfectant dosing by continuously monitoring chlorine residuals at the influent and effluent of the disinfection basin.[1] Real-time calculations of initial disinfectant demand and decay rates ensure precise and adaptive chemical dosing to meet disinfection targets while minimizing chemical waste. A lab-scale batch pilot system validated the ICT-based control strategy, demonstrating effective dose adjustments and disinfection performance. Future enhancements will integrate contact basin hydraulics into the digital twin framework to improve dose calculation accuracy by capturing basin dynamics and their influence on disinfection efficiency. The system's innovations, including dynamic dose control and predictive simulation capabilities, position it as a transformative solution for sustainable wastewater treatment.

## Materials and Methods

As illustrated in Figures 1 and 2, a lab-scale batch pilot system was developed, comprising a dose controller, chemical injection pump, disinfectant analyzer, recirculation pump, and reactor. The system operates with a 32 L working volume, calculating chemical dosage based on demand and decay rates from the previous cycle to meet target ICT levels. The automated system follows a predefined sequence: flushing with fresh water, draining, filling with secondary effluent from treatment plant, dosing, mixing, analyzing disinfectant residuals, draining, and repeating the cycle. Real-time data collection during each cycle informs demand and decay rate calculations.

ICT, demand and decay calculation method was validated by comparing two different calculation methods, including linear regression method embedded in the dose controller and second-order reaction equations solved using Excel Solver. The linear regression method does the calculation on intercept (demand) and slope (decay) based on the second-order reaction, while second-order reaction models optimize demand and decay rates by minimizing discrepancies between calculated and measured disinfectant concentrations. Data logged by the dose controller during each cycle were used for both calculation method comparisons.

Pathogen analysis, including fecal coliform measurements, evaluated disinfection efficiency to ensure compliance with a 2-log reduction target. These results were used to establish the target ICT for pathogen inactivation compliance. Testing was conducted over 24 cycles under varying water quality conditions and dose concentrations. Samples for pathogen analysis were collected from the recirculation loop at 0, 5, 10, 20, 30, 40, and 60 minutes.

**Figure 1** A lab-scale batch pilot system (Side-Stream system)

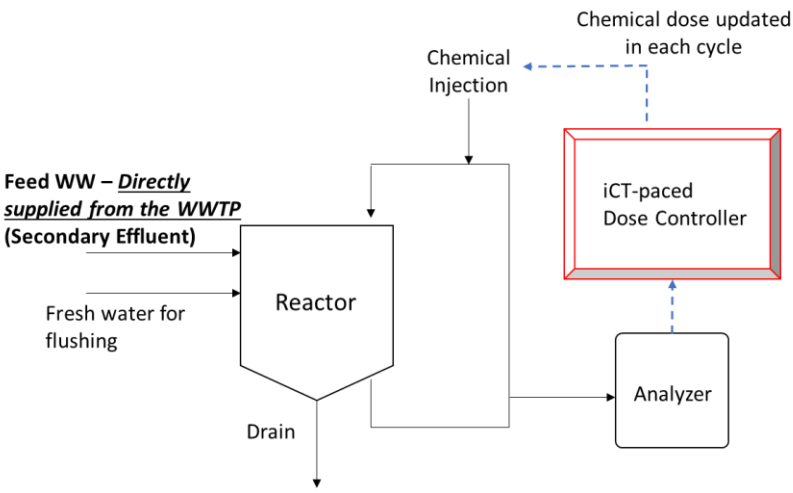


**Figure 2** Schematic of a lab-scale batch pilot system

**Results and Discussion**

In this study, sodium hypochlorite was used as disinfectant. Data collected over 24 cycles were processed and compared using two different calculation methods, as shown in Figure 3. The high correlation between methods ($R^2 \approx 1$) demonstrates the accurate and reliable functioning of the ICT calculation approach implemented in the dose controller. These results indicate that demand and decay calculations were performed accurately. Since the tests were conducted on different dates and with varying dose concentrations, it can be inferred that the ICT calculation method effectively adapts to changing water quality conditions and maintains robust performance.

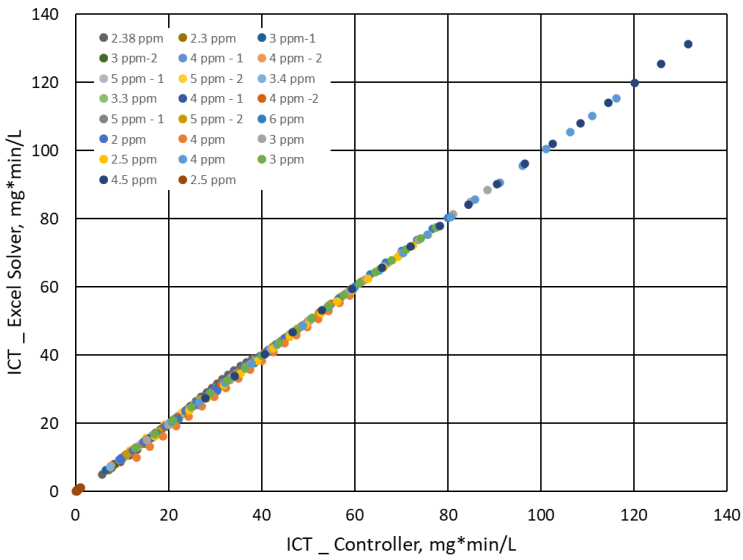


**Figure 3** Comparison of calculated iCT between controller and excel solver

The log reduction (LR) of fecal coliforms was plotted against ICT values, revealing clear trends that support effective disinfection at appropriate ICT levels. The Greenway Wastewater Treatment Plant's secondary effluent ICT was determined to be approximately 20 mg*min/L.

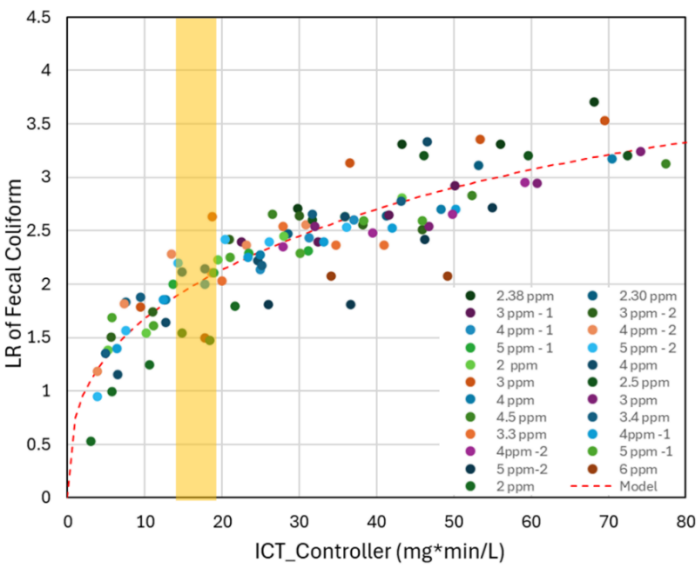


**Figure 4** Pathogen analysis results

As shown in Figure 5, ICT monitoring was based on a target ICT of 40 mg·min/L, a value derived from previous bench tests under poor water quality conditions. The graph demonstrates that ICT was well maintained during operation. Fluctuations in values correspond to validation test dates where dosing was manually controlled. This highlights the system's adaptability and accurate response to operational changes, ensuring effective disinfection performance.

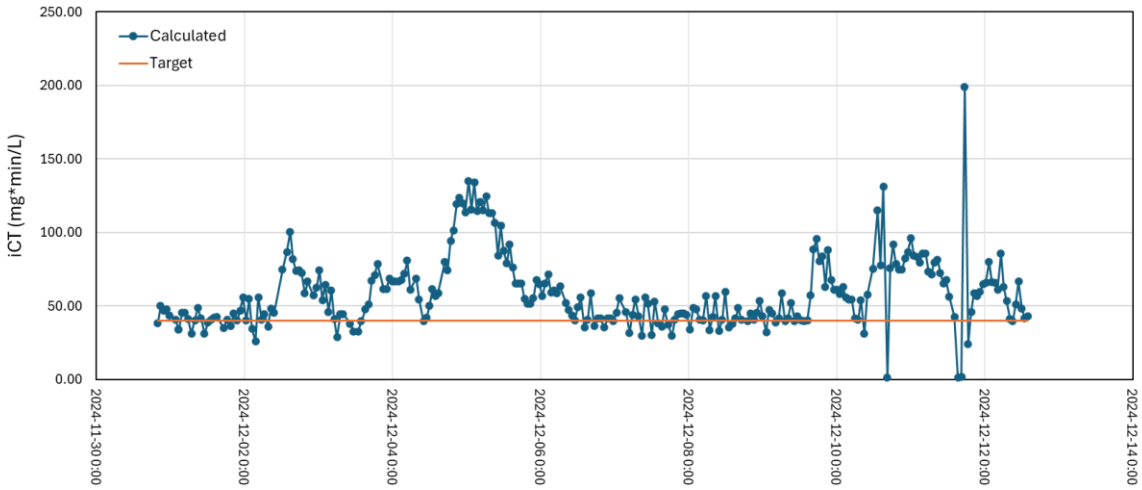


**Figure 5** ICT monitoring results

**Conclusion and Future work**

These findings validate the ICT calculation methods and their effectiveness in maintaining disinfection standards and target ICT levels, even under variable operational conditions. The robust system performance demonstrated in this study establishes a strong foundation for integrating the ICT-based framework into digital twin models for wastewater disinfection. Future studies will focus on scaling up the side-stream pilot system for full-scale applications, incorporating contact basin hydraulics into the framework, and further refining process optimization through enhanced digital twin integration.

This research successfully validated an ICT-based smart dose control framework using a lab-scale pilot system, demonstrating effective real-time dynamic dose adjustment, efficient disinfection, and minimized chemical use. The next phase of research will involve expanding the system for full-scale applications and leveraging the comprehensive digital twin framework for improved process optimization and operational efficiency.

## REFERENCES

1. K. Manoli, S. Sarathy, R. Maffettone, D. Santoro, 2019 Detailed modelling and advanced control for chemical disinfection of secondary effluent wastewater by peracetic acid, Water Res. **153**, 251–262