Journal of Applied Research and Technology

www.jart.icat.unam.mx

Journal of Applied Research and Technology 24 (2026) 564-574

Original

Design of a Monitoring and Coordination Setup for an Onsite Electrochemical Production of Sodium Hypochlorite

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Received: 03 12 2024; Accepted: 10 07 2025
Available: 31 08 2026

Abstract: This study presents the design and implementation of a fully automated system for precise sodium hypochlorite dosing, simulating an in situ generation plant. The system integrates a MATLAB-based human-machine interface (HMI) and a control unit connected to an Arduino UNO board, ensuring real-time monitoring and adjustment. An electrochemical method utilizing graphite electrodes and the LMP91000 integrated circuit was developed to determine hypochlorite concentration. Signal conditioning was achieved through digital and analog circuits, interfacing sensors, and actuators with the control system. The system demonstrated reliable detection and dosing performance with a resolution of 2 mg/L for sodium hypochlorite concentrations in the range of 2–12 mg/L, achieving complete dosing within the target concentration range. Experimental results validate the system's effectiveness in automatically regulating hypochlorite dosing, demonstrating its potential for water disinfection in resource-limited communities. A detailed calibration procedure is also provided to ensure operational reliability and accuracy.

Keywords: **automation system, human-machine interface, MATLAB, public health, sodium hypochlorite, sustainable development goals, water sanitation.**

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Peer Review under the responsibility of Universidad Nacional Autónoma de México.

1. Introduction

Access to safe and clean drinking water remains a global public health priority (Gómez-López et al., 2017). Among various disinfection methods, chlorination—particularly through sodium hypochlorite—has proven to be a simple, effective, and widely adopted strategy, especially in decentralized and resource-limited settings (O'Brien et al., 2005; Fei et al., 2022). Sodium hypochlorite generates free available chlorine (FAC) through hydrolysis reactions that produce hypochlorous acid (HClO) and hypochlorite ions (ClO^-), both potent disinfectants (Reilley et al., 2014; Clark, 2014). However, maintaining appropriate FAC levels is critical to ensure effective pathogen elimination while avoiding harmful byproducts (Witt & Reiff,1993).

Alternative disinfection technologies such as ozonation and ultraviolet (UV) irradiation offer strong microbial inactivation capabilities. Nevertheless, these methods often require complex infrastructure, higher energy inputs, and skilled operation, limiting their suitability for low-resource environments (Moerman., 2014). In contrast, electrochemical generation of sodium hypochlorite offers a scalable, cost-effective solution that can be integrated into automated, real-time control systems (Fei et al., 2022; Edzwald, 2011).

Despite its benefits, manual dosing and monitoring methods, such as colorimetric tests using DPD, are labor-intensive, subjective, and involve handling hazardous reagents (Kodera et al., 2004). These limitations highlight the need for automated supervision systems capable of dynamically adjusting disinfectant concentrations based on real-time water quality parameters (Zubiarrain-Laserna et al., 2022; Qin et al., 2015).

This paper presents the design and evaluation of an integrated monitoring and control system for an on-site electrochemical sodium hypochlorite generator. The proposed architecture incorporates sensors, actuators, and a user interface to enable closed-loop control of chlorine concentration, pH, and other relevant variables (Sharma, 2016). By integrating electrochemical sensing and programmable logic, the system ensures consistent disinfection performance while enhancing safety, accessibility, and cost-efficiency. This approach supports the development of sustainable, automated water treatment solutions aligned with current health and safety standards (Oficial, 1988; Allen et al., 2021; Mellou et al., 2022).

As part of its current development, this prototype was primarily designed to demonstrate automation capabilities and precise hypochlorite dosing control. While direct microbiological testing was not included in this phase, the abstract now indicates that the system achieves free chlorine concentrations within the range recommended by the World Health Organization (2–5 mg/L), suggesting a strong potential for effective disinfection. Future work will incorporate microbiological analyses to quantitatively assess pathogen removal efficiency.

The primary anodic reactions considered for hypochlorite generation from brine electrolysis include the oxidation of chloride ions to chlorine gas (Wang et al., 2023; Ferro et al., 2025).

$$2Cl^-(aq) \rightarrow Cl_2(g) + 2e^-, \quad Eo = -\,1.36\ V\ vs.SHE$$

followed by the subsequent hydrolysis of dissolved chlorine and its reaction with hydroxide ions (formed at the cathode) to produce hypochlorite: (Chen et al., 2024)

$$Cl_2(g) + H_2O(l) \leftrightarrow HOCl(aq) + H^+(aq) + Cl^-(aq), \quad Eo = 1.49\ V\ vs.SHE$$

and

$$Cl_2(g) + 2OH^-(aq) \rightarrow OCl^-(aq) + Cl^-(aq) + H_2O(l), \quad Eo = +\,0.29\ V\ vs.SHE$$

The potential competing anodic reaction of water oxidation: (Botte, 2017)

$$2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^-, \quad Eo = +\,1.23\ V\ vs.SHE$$

will also be noted.

The principal cathodic reaction is the reduction of water: (Das & Chen, 2024)

$$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq), \quad Eo = -\,0.83\ V\ vs.SHE$$

2. Materials and Methods

2.1 In situ Sodium Hypochlorite Generation Systems

Chlorine and hypochlorite are obtained by electrolysis of brine and saline solutions, which have remained attractive since the early twentieth century when a brine source was readily available (Edzwald, 2011). At the core of any in situ generation system lies an electrolytic cell, which performs the electrochemical production of chlorine (Casson & Bess, 2006; Kuhn & Lartey, 1975). Figure 1 illustrates the proposed signal flow for an in situ electrochemical sodium hypochlorite generation system. This electrooxidation process transforms sodium chloride brine (NaCl), used as the raw material in the in situ generator, into a disinfectant solution containing aqueous chlorine. Equation

1 represents the conversion of sodium chloride to sodium hypochlorite during electrooxidation (Reilley et al., 2014):

$$NaCl + H_2O \rightarrow NaClO + H_2(\text{gas}) \quad (1)$$

In an in situ generator system, as shown in Figure 1, the tank initially contains only sodium chloride. The sodium chloride concentration gradually decreases after the electrolysis process is successfully applied to the cell and recirculation. In contrast, the sodium hypochlorite concentration increases until it reaches a maximum value of 1%, as allowed by the nature of the reaction in that configuration.

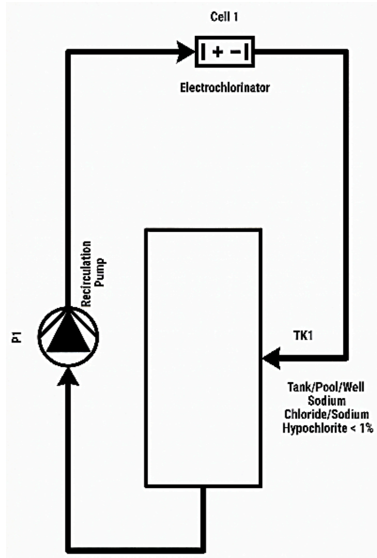


Figure 1. Signal flow chart for an in situ electrochemical sodium hypochlorite generator.

2.2 In situ Sodium Hypochlorite Dosing Systems

Sodium hypochlorite dosing systems comprise storage tanks equipped with dosing pumps (Barsotti & Hardy, 2009). In this process, a tank filled with chlorine-free water receives a controlled feed of the concentrated solution through the dosing pump, thus producing a diluted sodium hypochlorite solution in the tank. An agitating pump circulates and mixes the tank contents to guarantee a homogeneous mixture with a consistent chlorine concentration in the shortest possible time (Barsotti & Hardy, 2009). Figure 2 shows a representation of the dosing system.

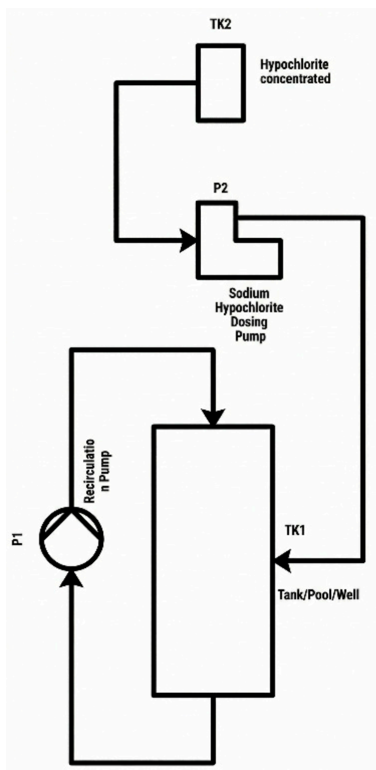


Figure 2. Signal flow chart of the dosing system.

2.3 Combined in situ generation and dosing systems for sodium hypochlorite

Enhancing the systems above can be combined into a unified system. In this configuration, hypochlorite is produced through electrolysis of brine, reaching the maximum possible concentration. Subsequently, the dosing system was administered in a precise amount to the final tank. The integrated proposal is shown in Figure 3.

2.4 Automation system: Supervision and control

The joint application of in situ generation and automatic dosing systems is recognized as a good practice for effective control of disinfectant concentrations, such as chlorine, in water.

These systems are monitored by sensors that measure residual chlorine levels and precisely adjust dosing to maintain adequate levels, thus ensuring water quality and potability, according to guidelines established by the World Health Organization (World Health Organization, 2006).

The system proposals presented for both in situ generation and dosing require appropriate control instrumentation for proper implementation (Barsotti & Hardy, 2009; World Health Organization, 2006). Generally, a process comprises a series of systematic actions aimed at a specific outcome. An automation system must be integrated to ensure the process runs automatically and delivers the desired results. This system comprises components to supervise and control the process and operates without manual intervention (Ogata, 2003).

The automation system is linked to the process through signals that are categorized into input and output signals. Input signals provide information on the behavior of the process, whereas output signals modify that behavior (Sharma, 2016). The automation system includes three primary components:

1. Instrumentation: Sensors and signal conditioners to measure process parameters.
2. Control system: Algorithms programmed into an Arduino UNO microcontroller to process input signals and regulate actuators.
3. Human-machine interface (HMI): A MATLAB-based real-time monitoring and user interaction application.

Figure 4 illustrates the basic structure of the automation system.

This research aligns with the United Nations Sustainable Development Goals (SDGs), particularly Goal 6: Clean Water and Sanitation, by promoting innovative solutions for disinfection in communities with limited access to potable water. Implementing an automated system for controlled sodium hypochlorite dosing ensures safe drinking water and reduces health risks associated with inefficient or inconsistent disinfection processes.

Additionally, this study contributes to Goal 9: Industry, Innovation, and Infrastructure, as it advances technological solutions that optimize chemical usage, improve safety in handling disinfectants, and enable real-time process monitoring. By integrating automation into water treatment, this work fosters sustainable and accessible solutions for public health and environmental protection.

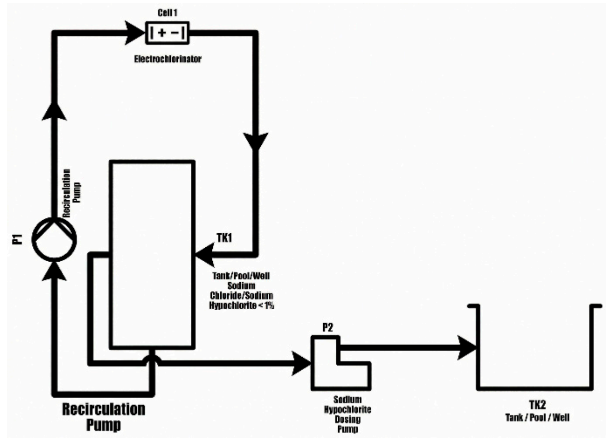


Figure 3. Signal flowchart for an in situ electrochemical sodium hypochlorite generator with a dosing system.

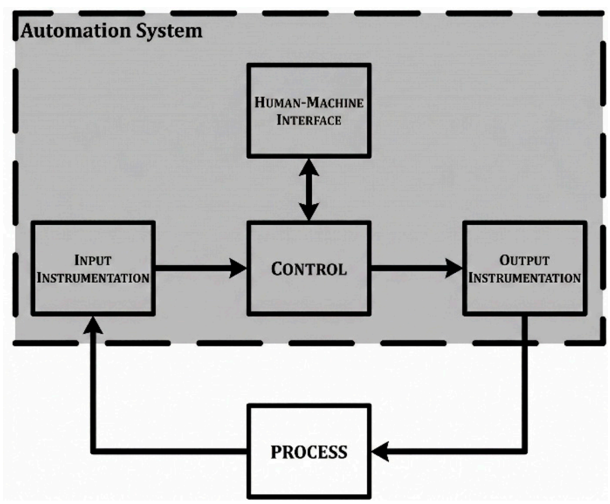


Figure 4. Structure of the automation system.

3. Results and Discussion

3.1 Automation system: Supervision and control

The developed automation system was implemented for a prototype sodium hypochlorite dosing plant, simulating an in situ generation plant. The human-machine interface (HMI) and control system were developed using a personal computer (PC) that runs a program in MATLAB (Barriola et al., 2024; Hamel & Rosales-Anzola, 2024; Inc, 2023; Karami, 2022; Mudhavath et al., 2024; Hernández, 2022; Hernández et al., 2024; Rosales-Anzola & Pérez-Hernández, 2023; Yeo, 2020). The instrumentation system consisted of a signal conditioning stage with digital and analog integrated circuits connected to a converter/actuator implemented on an Arduino UNO electronic board (Oo, 2020; Qomaruddin et al., 2024).

This process involved a tank containing a diluted sodium hypochlorite solution at a specific concentration. Automation aims to achieve the desired chlorine concentration in a predetermined volume of water without requiring manual intervention beyond the initial activation process. The input signal is hypochlorite concentration, whereas the output signals include multiple operations, such as hypochlorite dosing, agitation, sampling, acid dosing, taking measurements, and sample cell drainage. Figure 5 illustrates the basic structure of the automation system.

3.2 Instrumentation

The constructed instrumentation system is shown in Figure 6, which shows the components of its structure.

3.3 Functional components of the input instrumentation system

3.3.1 Converter

The converter aims to enhance the quality of the conditioner's signal and adapt it for transmission to the control system. An ADC, a USART, and a USB-Serial Converter are utilized on an Arduino UNO board, which includes a microcontroller integrating a 10-bit ADC and a USART, along with a USB-Serial converter chip and a USB type-B connector. This Converter stage is implemented in an input instrumentation system.

3.3.2 Input signal conditioner

A potentiostat, LMP91000 from Texas Instruments, is used as the analog "front-end" circuit to amplify and filter signals from electrochemical sensors (Bhunia et al., 2015). LMP91000 is programmable via I2C, simplifying its connection to the microcontroller on the Arduino UNO board. The same microcontroller was also implemented in the actuator stage of the output instrumentation system. Cell polarization is conducted digitally, and the analog current output serves as the input to the ADC in the converter stage. The LMP91000EVM is an evaluation module that features the LMP91000 integrated circuit on a manageable PCB, providing easy access to all its pins and allowing, for instance, a connection to a microcontroller. A potential scan was carried out over a 4KΩ resistor to test the device, as shown in Figure 7.

3.3.3 Sensor Element

An electrochemical system was constructed to measure the concentration of hypochlorite. The electrochemical cell used was a three-electrode system (Kabir et al., 2019):

- Graphite disk working electrode (WE).
- Silver/silver chloride (Ag/AgCl) in a 3 M sodium chloride solution (3 M NaCl) as the reference electrode (REF).
- Graphite rod as the counter electrode (CE).

To determine the hypochlorite concentration (Pungor et al., 1970), a potential difference of -0.4 V is established between WE and REF. The current reduction of the dissolved gaseous chlorine was measured at pH < 0.5. This current is proportional to the hypochlorite concentration.

3.3.4 Functional components of the output instrumentation system

In this stage, an actuator is used in the output instrumentation system to transform the output command signals

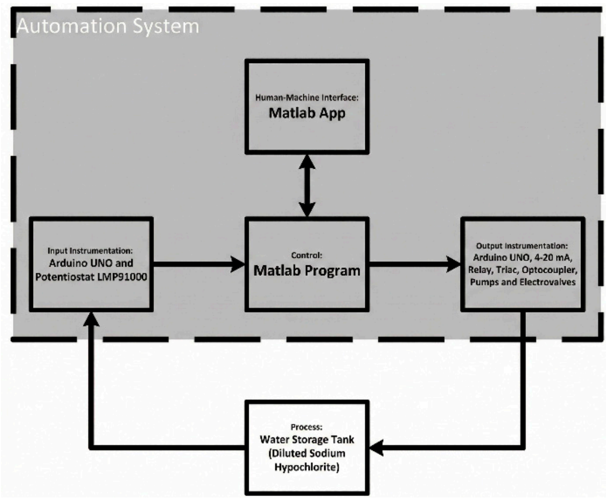


Figure 5. Basic structure of the automation system.

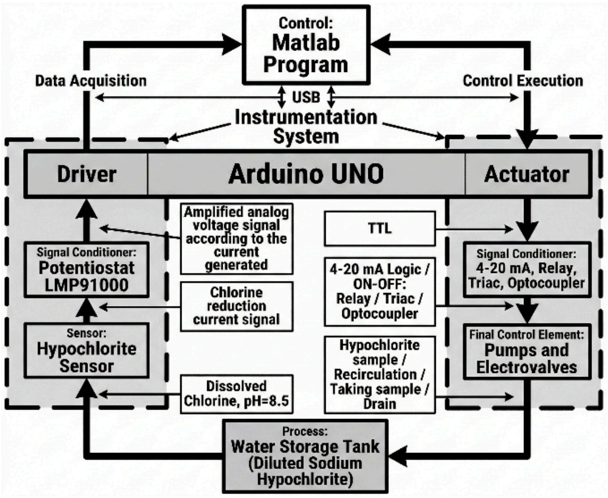


Figure 6. Structure of the instrumentation system.

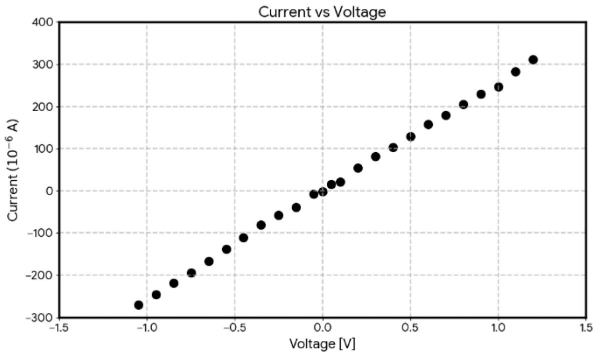


Figure 7. Potential scan conducted over a 4KΩ resistor.

from the control system into a suitable signal for the signal conditioner.

In this stage of output signal conditioning, the necessary electronic circuits were built to convert the signals from the actuator's TTL logic into suitable signals for each of the final control elements comprising the following stage. All circuits were simulated in LTSpice, such as the optically isolated circuit that transmits on/off signals to the peristaltic pump, the 4-20 mA logic circuit that sends on/off signals to the dosing pumps, a relay circuit that sends on/off signals to the solenoid valves, a Triac circuit that controls the stirring pump, and a source circuit designed to provide all the required voltages for the circuit power supply.

3.3.5 Final Control Element

The elements in this stage include the following:

- Hypochlorite Dosing Pump: This pump applies the sodium hypochlorite dose or aliquot to the process according to the calibrated flow rate each time it receives a command from the control system in the form of a 20 mA logic signal. Model: LMI Milton Roy Metering Pump with Micropace Accessory.

- Agitation Pump: This pump functions as a recirculation pump. After a specific flow of hypochlorite is dosed into the process, it receives an ON signal from the control system. This ensures the condition of homogeneity or "continuous agitation" (CSTR) in the diluted hypochlorite tank, allowing the problem to be approached from the perspective of concentrated rather than distributed parameters. Model: Generic washing machine drainage pump.

- Peristaltic Pump: Used to collect a sample from the problem tank and add it to the electrochemical cell. Model: Cole Palmer L/S series.

- Acid Dosing Pump: This pump administers a specific amount of hydrochloric acid to the electrochemical cell, adjusted according to the flow rate previously calibrated. It is activated each time it receives an order from the control system, expressed as a 20 mA logic signal. The necessary amount of acid was added to ensure a pH < 0.5 for the measurement. Model: LMI Milton Roy Metering Pump, with Micropace accessory.

- Solenoid Valve 1, Venturi Tube, and Solenoid Valve 2: These three elements were used to manage the drainage of the electrochemical cell. A solenoid valve is connected directly to the bottom of the cell. When the valve was electrically activated, the pressure of the solution in the cell was not high enough to open the valve. To resolve this issue, the solenoid valve's output was directed towards the vacuum port of a Venturi tube. The second solenoid valve allowed water to pass and activate through the Venturi tube. Figure 8 shows the setup.

3.3.6 Control

The structure of the control system is shown in Figure 9, including the automation strategy and the data interfaces with the instrumentation system and the human-machine interface. The control algorithm is presented in the flowchart shown in Figure 10.

3.3.7 Automation Strategy

Due to the sensor's non-continuous measurement, sequential discrete control with an intermediate condition ("interlock") was implemented.

3.3.8 Human-Machine Interface

A MATLAB App Designer application was programmed to implement the human-machine interface. The application comprises several tabs, including the one called Automated Dosing, which allows access to the main window of the dosing system, as shown in Figure 11(a). In this window, the following user variables are entered: concentration of the NaClO working solution (mg/L), desired concentration (mg/L), and initial volume of the reservoir (L). Pressing the Start button initiates the dosing process and concludes when the desired concentration is reached. The Manual Mode tab is used for system calibration, as shown in Figure 11(b).

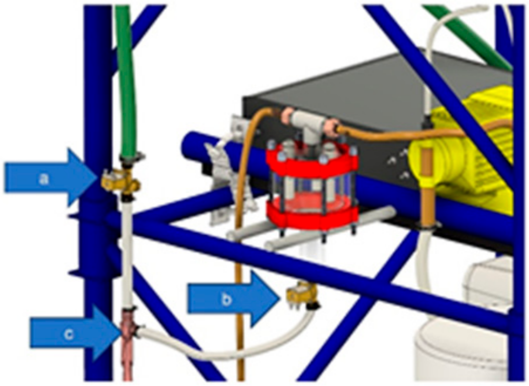


Figure 8. Arrow points to (a): Solenoid Valve 2, (b): Solenoid Valve 1, c: Venturi Tube generating vacuum.

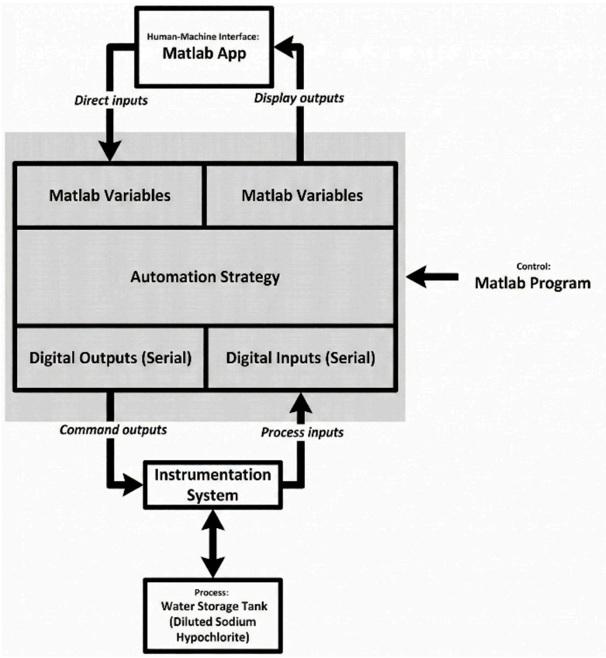


Figure 9. Structure of the control system.

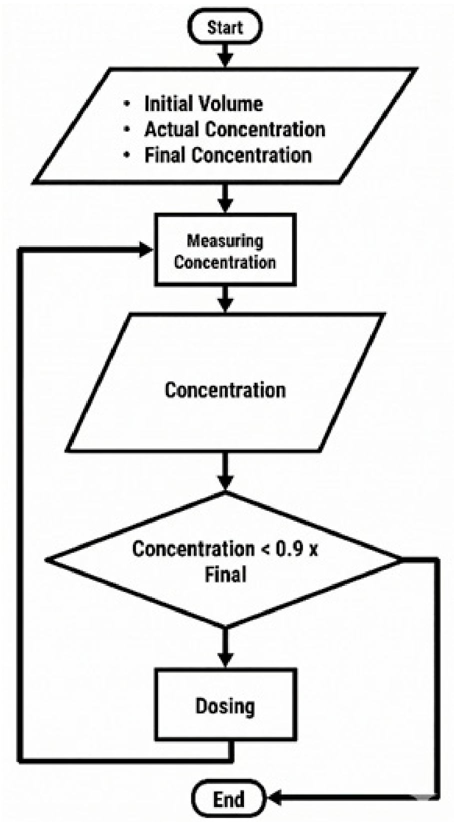
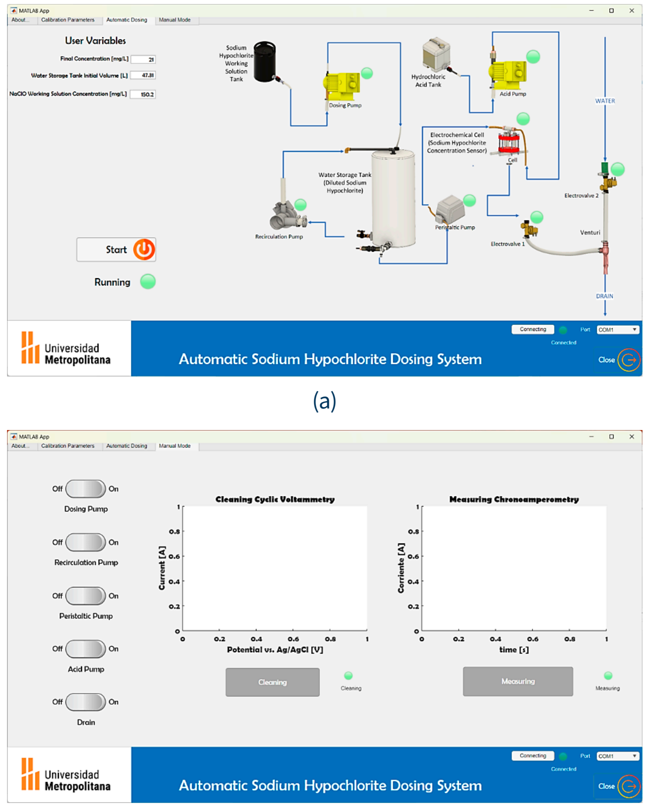


Figure 10. Flowchart of the control algorithm.



(a)

(b)

Figure 11. User interface of the automation system: (a) "Automated Dosing" tab and (b) "Manual Mode" tab.

3.3.9 Design and Construction of the Automation System

An automated process prototype was designed and constructed; its 3D image is shown in Figure 12.

3.3.10 Calibration of the Chlorine Dosing Automation System

The steps followed for the calibration are as follows:

- Two sodium hypochlorite solutions with concentrations of 2 ppm and 10 ppm, without HCl, were prepared using measurement strips or DPD tablets as references to verify them. N, N-Diethyl-p-phenylenediamine (DPD) is a standard colorimetric meter applied to a commercial kit's control container. Chlorine concentration is determined by comparing the acquired color with the scale. (1 ppm = 1 mg/L).

- Sodium hypochlorite solutions (500 mL) with concentrations of 2 ppm and 10 ppm at pH = 0.5 were prepared in triplicate using HCl.

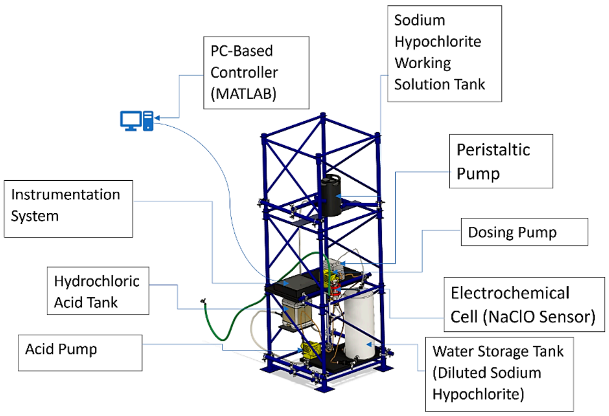


Figure 12. Prototype plant design. Elements of the automated system for the chlorine dosing process.

- All electrodes were placed in the cell, measurements were taken using the program in manual mode, Figure 11(b), and the current values obtained were recorded and saved as calibration data.

- The cell was emptied, and measurements were taken for at least five days.

Our system achieves performance levels comparable to other electrochemical disinfection systems reported in recent studies.

The design demonstrates high effectiveness within the range of established decentralized chlorination technologies. Additionally, it offers advantages in terms of lower energy consumption and capital cost when compared to alternative disinfection methods such as ozonation and UV-based systems (Alkhadra et al., 2022; Brdarić et al., 2024; Ferro et al., 2025; Jin & Adhikari, 2025; Zhanget al., 2023).

Conclusions

This study successfully developed and implemented an automated system for the in situ generation and dosing of sodium hypochlorite, addressing key challenges in water disinfection. A simple and effective electrochemical method using graphite electrodes was designed to measure hypochlorite ion concentrations, ensuring process efficiency by carefully considering dosing time and control capacity. The system integrates electrochemical sensors, an Arduino-based control unit, and a MATLAB-designed HMI, demonstrating reliable performance in maintaining precise chlorine concentrations.

Experimental results validated the scalability and potential of this system for application in resource-limited settings, offering a cost-effective and safe solution for water disinfection. The full-scale automated dosing prototype has valuable potential for community tank disinfection, particularly in areas without continuous access to potable water. Thorough biochemical analysis and further analytical chemistry validation are recommended to assess the system's accuracy and precision, showing a resolution of 2 mg/L for measurements between 2 mg/L and 12 mg/L.

Future developments could incorporate IoT (Internet of Things) technologies to enable remote monitoring, real-time alerts, and enhanced operational control, minimizing manual intervention and reducing operational risks. This work underscores the importance of accessible and scalable water treatment technologies, emphasizing their role in improving public health and quality of life in underserved communities.

The prototype developed represents an efficient, affordable, and accessible solution for the electrochemical generation and automated dosing of sodium hypochlorite in water disinfection. Its modular design, ease of integration, and consistent performance support its suitability for decentralized applications, particularly in resource-limited settings. Future work will focus on field validation and long-term durability assessments to further enhance system reliability and scalability.

Acknowledgements

The authors acknowledge the support from Universidad Metropolitana (UNIMET), Departamento de Energía y Automatización, Decanato de Investigación y Desarrollo Académico y Decanato de Ingeniería. This article is associated with project PG-A-19-21-22 of the Universidad Metropolitana (UNIMET).

Funding

The author received no specific funding for this work.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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