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Web-Based SCADA: Data Acquisition, Control and Energy Monitoring of Dryers

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Abstract

To sustain manufacturing processes, industrial companies demand continuous and reliable power sources. Subsequently, forecasting future power demands, alongside constant fault monitoring, requires real-time decisions that only data-driven systems can make for cost-effective production. Hence, this study's main interest was on developing a web-enabled Supervisory Control and Data Acquisition or SCADA, a system that can control, monitor power, and acquire datasets from a dryer. The proposed system undertook a variety of tests to confirm the specific features of interoperability, security, accuracy, and accessibility. In addition, in the various drying activities, the process values: Inlet Process Variable (InletPV) and Power Process Variable (PowerPV) datasets have been successfully generated and confirmed to have a strong link. Results proved that the proposed system performed well in all trials. These findings solidify the systems' industrial scalability and further recommend enhancing other security aspects for other drying tasks in sensitive environments. Overall, this study provided a basis for superior control, monitoring, and data analysis on industrial drying processes, thereby minimizing dependence on expensive brand-specific hardware, improving user accessibility, predicting future power costs and faults, resulting in better control.

***Keywords**:* data acquisition, energy monitoring, industrial dryer, web-enabled SCADA, wireless control

1. Introduction

The main feature of a Supervisory Control and Data Acquisition (SCADA) system is displaying system components through icons, monitoring real-time values, and controlling various devices (Filková and Mujumdar, 2020). Over the years, these systems have become much more accessible, flexible, and scalable, mainly because of the integration of different available technologies.

Specifically, incorporating web technologies has enabled remote access and enhanced real-time monitoring. As a result, it is now possible to shorten iteration cycles, ensuring product quality while improving process efficiency (Kavitha and Vallikannu, 2019). Moreover, the live information available has facilitated collaborative decision-making and better process optimization (Sahoo and Goswami, 2023), connecting people across organizational levels, from top management to field operators. Consequently, this has made SCADA one of the most efficient monitoring and control systems in today's manufacturing environment.

1.1 Industrial Drying

In general, depending on the type of material, most drying processes produce dried products by removing specific percentages of moisture. Additionally, several heat transfer modes used in commercial drying, such as conduction (Sampath *et al*., 2025), convection (Zheplinska *et al*., 2021), radiation (Delfiya *et al*., 2022), and dielectric heating (Miyakawa *et al*., 2021), achieve high-quality, large-throughput products while reducing production costs and increasing profitability (Martynenko and Vieira, 2023; Kabeyi and Olanrewaju, 2023; Arias *et al*., 2023). However, depending on the scale and nature of production, electricity and gas are required to maintain drying operations. Furthermore, electrically powered dryers are more common due to better control, safety, and lower global carbon footprints (Hassan *et al*., 2024; Alagoz and Alghawi, 2023). Therefore, industries adopt strategies to support low-energy, high-throughput operations through heat recovery systems (Khayyam *et al*., 2021), passive heat transfer (Ajarostaghi *et al*., 2022), renewable energy (Acar *et al*., 2022), and advanced monitoring and control technologies such as IoT (Dinesh *et al*., 2022; Dadhaneeya *et al*., 2024; Komanee *et al*., 2025) and SCADA (Putra *et al*., 2024; Syahid *et al*., 2024).

1.2 Web-Based SCADA Systems

Industrial drying processes equipped with cutting-edge power monitoring and control features (Stankov, 2024) can be done through web-enabled SCADA. Furthermore, some notable features included digitalization of controls (Adeyanju *et al*., 2021), improved component visualization (Tcaciuc-Gherasim, 2022; Maldonado-Correa, 2020; Gomez, 2019), and systematic monitoring of processes. However, these systems remain costly, mainly due to hardware complexity (Nazarova *et al*., 2022), software configuration (Elgbacka, 2024), and limited data access (Ara, 2022) for each manufacturer.

To address this, manufacturers developed a standard called OPC UA (Open Platform Communications Unified Architecture) to handle data-access issues more effectively (Busboom, 2024). However, some studies have shown that implementing the OPC-UA standard across brands increases vulnerability to cyberattacks (Yaben and Vasilomanolakis, 2025; Srivastava *et al.*, 2023), creates scalability limitations (Osman *et al.*, 2022), and hinders interoperability (Ladegourdie and Kua, 2022). To overcome these challenges, leveraging internet-based technologies allows machines to generate digital footprints of their active parameters, providing real-time monitoring (Babayigit and Abubaker, 2023; Shinozuka *et al.*, 2020), enabling anomaly detection (Chen *et al.*, 2021), and supporting predictive control—features that depend on high-quality datasets. The main advantage is the availability of ready-to-download datasets that can be used across different platforms for energy analysis (Ponte *et al.*, 2024), predictive maintenance (Udo and Muhammad, 2021), and performance optimization (Vanalakshmi *et al.*, 2023), facilitating the effective use of new technologies.

1.3 SCADA System Design

Power monitoring is one of SCADA's essential features, designed to cut costs and detect faults in manufacturing environments. These faults (Mitra and Koley, 2024; Harrou *et al.*, 2023), whether identified manually or automatically, are crucial for maintaining equipment (Liu *et al.*, 2021), predicting failures (Turnbull *et al.*, 2021), and avoiding process shutdowns. Real-time energy data (Vale *et al.*, 2015; Tomar *et al.*, 2023) can be used to optimize controls (Syahid *et al.*, 2024; Yadav *et al.*, 2023; Maureal *et al.*, 2024) and monitoring (Babayigit and Sattuf, 2019; Parilla *et al.*, 2020), leading to sustainable energy use and lower risks (Ghosseini *et al.*, 2023; Ponte *et al.*, 2024). In supporting renewable energy use (Qays *et al.*, 2022), SCADA has proven effective in maintaining power at optimal levels.

High-performance control has been one of SCADA's key features. To enhance these capabilities, SCADA frameworks are continuously being improved with new algorithms to optimize their processes (Liu *et al.*, 2020). Additionally, 21st-century technologies like machine learning have become popular for SCADA's predictive control in many drying operations (Gomez and Caballero, 2023; Barriga *et al.*, 2023; Rakholia *et al.*, 2025). Consequently, improved temperature and humidity control have resulted in less production waste, leading to higher-quality dried products (Ali *et al.*, 2021).

Long-term reliability can only be achieved by having consistent and accurate data. For a typical SCADA system, its devices could be interpreted as abnormal if their values frequently become inaccurate or inconsistent (Zhaoqian *et al.*, 2022). Moreover, aside from sensor errors, these data inaccuracies could be interpreted as a possible security issue (Rakas *et al.*, 2020) predominant in internet-connected environments. Highlighting these data anomalies describes why the existing SCADA system features should be further investigated to reduce cybersecurity risks (Andrade *et al.*, 2022).

1.4 Future Directions and Challenges

The integration of web technologies with SCADA frameworks offers many opportunities for advancing industrial dryers. However, as commercial products increasingly vary over time, industrial manufacturing must also adapt to meet the evolving market demands and help mitigate energy crises. Achieving data interoperability and accessibility (Nechibvute and Mafukidze, 2024; Vaduva *et al.*, 2022), along with implementing appropriate cybersecurity measures (Gunnarsson, 2023; Alanazi *et al.*, 2023) and efficient version control (Ager and Bergman, 2024), has become essential, especially as wireless technologies like IoT (Putra *et al.*, 2024; Viviane *et al.*, 2023) become more prominent. Additionally, Industry 4.0 technologies such as Big Data, Blockchain, and Artificial Intelligence can also contribute to system improvements (Sestino *et al.*, 2020). These efforts aim to address common challenges of SCADA systems, ultimately boosting the sustainability and efficiency of industrial drying processes. This combination of initiatives led the author to the main goal of this study: to develop a new web-based SCADA system for industrial dryers capable of wirelessly providing an interoperable, secure, and accurate dataset accessible through standard web browsers. Additionally, the study aims to analyze how the dryer's Inlet Process Variable (InletPV) influences the Power Process Variable (PowerPV), which is critical for effective real-time control and power monitoring of the dryer.

2. Methodology

This study focused on developing a web-enabled SCADA for an industrial dryer, specifically a spray dryer with a two-liter production capacity per set. The dryer was interfaced with the proposed web-based SCADA system.

2.1 Research Design

Figure 1 depicts the Spiral Model development method, which was chosen for this study because of its rapid iteration cycles and reliable design-build-test relationships. This strategy uses several brief repetitions to generate more responsive product development.

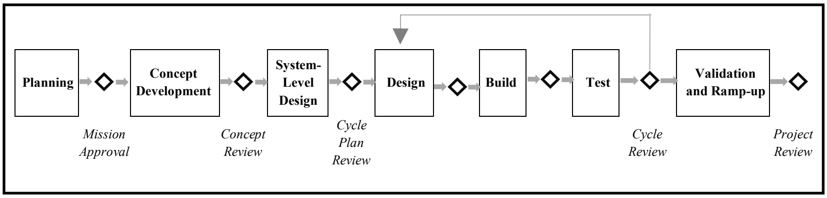


Figure 1. Development Process of the System (Mesa *et al*., 2019)

2.2 Requirements Analysis

To determine the specific requirements beyond those cited in the literature review, a practical validation was conducted with specialists: fifteen from the industry and fifteen IT professionals from various manufacturing sectors in the CALABARZON region, Philippines. These participants shared their insights during discussions to identify the necessary features for the proposed web-based SCADA system, specifically for dryers. Collectively, the specialists recommended including simple real-time control and power monitoring. They also noted that the proposed innovative features, such as wireless dataset generation, are not typically found in their current SCADA systems but could be a game changer for investigating department-level maintenance and energy audits. Based on this feedback and the information available in the literature, the selected features were finalized and evaluated using four key performance criteria: interoperability, security, accuracy, and accessibility. In addition to confirmatory use of datasets, further analysis was intended to measure the dryer under investigation.

2.2.1 Data Interoperability

This part of the web-based SCADA system involves whether the dataset generated remains compatible when interfaced across platforms. To achieve this, the system's responsiveness, measured through Mean Average Response Time (MART), was used to determine the interaction speed between the actors and the user interface (UI) during random drying operations as shown in Equation 1:

$$MART = \frac{1}{n}\sum_{i=1}^{n} RT_i \quad (1)$$

Where:

n = number of response time samples
RT_i = response time of the i^{th} transaction/request

Table 1. Response Time Classification

Response Time (ms)	Classification	Interpretation
< 100	Excellent	Feels swift to users; ideal for real-time systems (Adam, 2021).
100–499	Good	Generally conceived as fast and common for most web applications (Abadi *et al*., 2021).
500–999	Fair	Noticeable delay, but still usable (Chen *et al*., 2021).
1000–2000	Not Good	Lag can be felt; it can be used in non-critical real-time systems only (Martínez *et al*., 2023).
> 2000	Poor	Leads to user abandonment and higher cyber-attack risk (Kashevnik *et al*., 2020; Sikora *et al*., 2021).

Furthermore, the computing performance, as illustrated in Table 1, was evaluated using a latency test that measured the delay in transferring information from the field sensors to the user interface (UI) display (Shukla *et al*., 2023). Comma-Separated Values (CSV) format was also selected for its widespread compatibility with most web platforms (Nayak *et al.*, 2021).

2.2.2 Security

To reduce security risks when accessing the web server, discrete authentication was implemented through a login page. To restrict the actor's specific access to features and information within the system, authorization methods were also necessary. To prevent other actors' accounts from having passwords copied directly from the device after use, hashing procedures (Boonkrong, 2021) were integrated into the proposed SCADA. These features form the well-designed user interface (UI) of the functional login page with Role-Based Access Control (RBAC) and password encryption.

2.2.3 Accuracy

To directly determine the accuracy of the values reflected in the displays, a paired t-test statistical method was utilized. Since the measurement was intended to secure industrial quality control, a 99% confidence interval was chosen. For the sampling procedure, the entire population consisting of sensor values and the output dataset was compared to check discrepancies, as shown in Equation 2:

$$t = \frac{\bar{d}}{SD/\sqrt{n}} \tag{2}$$

where:

$\bar{d}$ = paired differences of mean
SD = standard deviation
n = number of pairs
t = t-statistic

2.2.4 Accessibility

This feature, measured by the mean average response time, dictates the capability of the system to acquire data within an acceptable time span after confirming security checks. Also, it entails the system's ability to be interoperable when accessed with different platforms (Corradini *et al.*, 2022) and multiple devices (Soszynski, 2025). To test the system, an automated end-to-end response time was evaluated using a combination of automation testing tools across different devices, covering both frontend and backend aspects of the system. Platforms used included BrowserStack Local (cross-browser response), Selenium (UI responsiveness), and Postman (Server/API response). Through these developments, dependence on typical SCADA brand-specific configurations for both hardware and software was reduced.

2.2.5 Process Insights

To better understand the effects of inlet temperature on the dryer's power usage, a scatter plot was used to illustrate the trend visually. To quantify the relationship between InletPV (inlet temperature) on PowerPV (energy use) over time, a multiple linear regression method was applied as shown in Equation 3:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon \tag{3}$$

Where:

Y = dependent variable (e.g., power consumption)
$X1, X2, \ldots X_n$ = time, inlet temperature, and power values
β_0 = Intercept (value of Y when all $X_i = 0$)
$\beta_1, \beta_2, \ldots, \beta_n$ = Coefficients that represent the effect of each variable on Y
ε = Error term (unexplained variance)

3. Results and Discussion

The mini-spray dryer, as shown in Figure 2, was incorporated with a web-enabled SCADA system, a depiction of numerous devices connected to the same wireless network. The control and monitoring functions of the spray dryer were added using the newly designed SCADA system shown on the touch panel, which can also be accessed by logging in via a web server.

Figure 2. Spray Dryer and Web-Based SCADA

3.1 Data Interoperability

The system's responsiveness was measured using the mean average response time (MART). System actors, such as the admin, user, and operators, accessed the system pages, including the login page, control page, and heat trends, during random drying operations. As shown in Figure 3, the system pages demonstrated good performance in terms of the average response time: the *login page (526.33±20ms), control page (366.33±8ms*), and *heat trends page (544.67±32ms)*. Furthermore, through algorithm optimization, the system exhibited the crucial role of the control page's real-time function, where dryer devices swiftly respond to the actors' commands via the user interfaces. The login page, which processes authentication, authorization, password hashing, and data exchange with the system's database, performs relatively slower than the control page due to its complexity. Meanwhile, the heat trends page exhibited an acceptable response time but behaves the slowest among other system pages, as it graphically updates page data that was increasing over time. This page was also where datasets, such as InletPV and PowerPV, were mostly downloaded for further analysis involving larger algorithm processing.

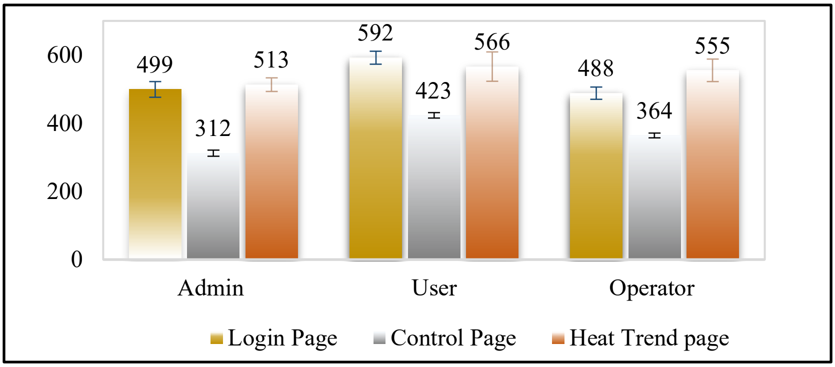


Figure 3. Data Interoperability of User Interfaces (UI) across Actors

As shown in Figure 4, the end-to-end data latency of dryer devices across the User Interface (UI) of the system pages, Login page (*421.4±37ms*), Control page (*417.48±36*), and Heat trends page (*484.96±24ms*), suggest the mean average response time (*441.21±33ms*) indicates good data latency performance across the different system pages of the web-based SCADA. Compared to other devices with a single piece of information per request, the microprocessor, despite a fair performance on the login page (504.36ms), shows a slightly higher latency due to the larger volume of information it carries through a single device channel. Such data includes the microprocessor's Temperature, RAM usage, CPU load, and disk activity. In addition, other factors that could usually expand latency performance include reducing hardware limitations of wireless access points, bandwidth, and minimizing signal noise.

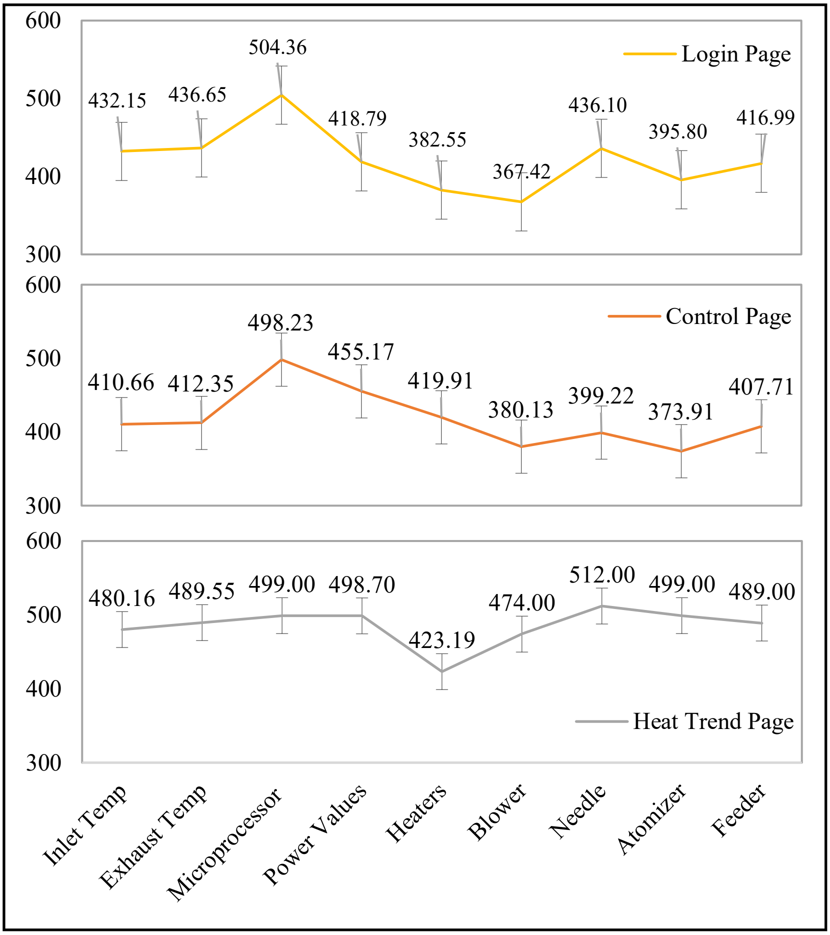
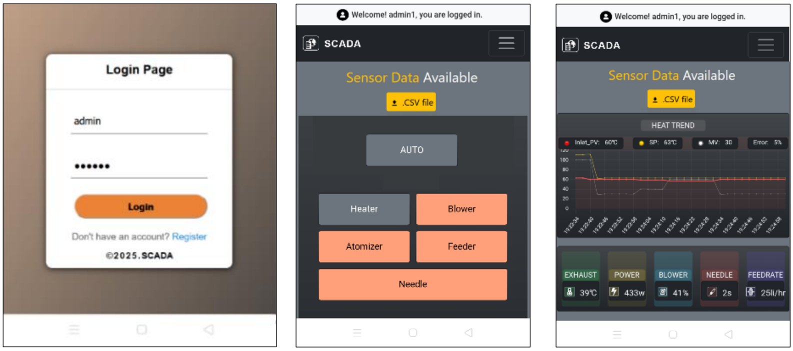


Figure 4. Data Latency Performance

3.2 Data Security

The functional log-in page, as shown in Figure 5a, authenticates the actors, whether they log in as an administrator, user, or operator, through their pre-defined username and hashed passwords, which may prevent database hacking. The system also employed Role-Based Access Control (RBAC), where these actors have selective use-cases where they were authorized to perform. As shown in Figure 5b, a functional control page where actors can manipulate devices associated with the dryer in real-time. The heat trends page in Figure 5c demonstrates an effective graphical representation of the inlet temperature, power, and other dryer process values. It was also observable in both Figure 5b and 5c that the dataset, in CSV format, was readily available for downloading.



(a) (b) (c)

Figure 5. System Pages: login page (a), control page (b), heat trend page (c)

Table 2. UML Class, Type, and Role

Class	Type	Description
Administrators	Actor	These are personnel within the organization who perform managerial functions.
Users	Actor	These are assigned personnel in charge of the recording process of data.
Machine Operators	Actor	These are assigned personnel in controlling the dryer.
Register	Use-Case	To register as a user of the SCADA system.
Login	Use-Case	To log in an actor.
Monitor Microprocessor	Use-Case	To monitor the microprocessor's performance.
Control Devices	Use-Case	To control dryer devices.
Monitor Process Values	Use-Case	To monitor dryer process values.

The Unified Modelling Language (UML) class, type, and roles shown in Table 2 represent the relationship between the Web-based SCADA system and the actors, such as the administrators, users, and operators. Administrators are top and mid-level management, composed of managers, supervisors, system developers, or line leaders. They can control the system's authentication and authorization procedures, monitor and control drying operations, perform planning and intervention, and recommend changes to the features. In contrast, the users, who can be further categorized into new or existing, were employees who perform control and data analysis on the performance of the microprocessor and the dryer in general. Lastly, the machine operators typically consist of personnel located in the field who are responsible for operating and monitoring the actual dryers.

The diagram shown in Figure 6 represents the graphical representation of the actors and the use cases within the system. The administrator can predominantly perform all use cases of the web-based SCADA, including registering users, logging in, monitoring microprocessor status, controlling devices, and monitoring process values. On the other hand, an existing user may also execute most use cases, except for registering new users, which is exclusively authorized by the administrator. Consequently, the machine operator was limited to monitoring and controlling operations, either directly on the dryer or wirelessly through the system.

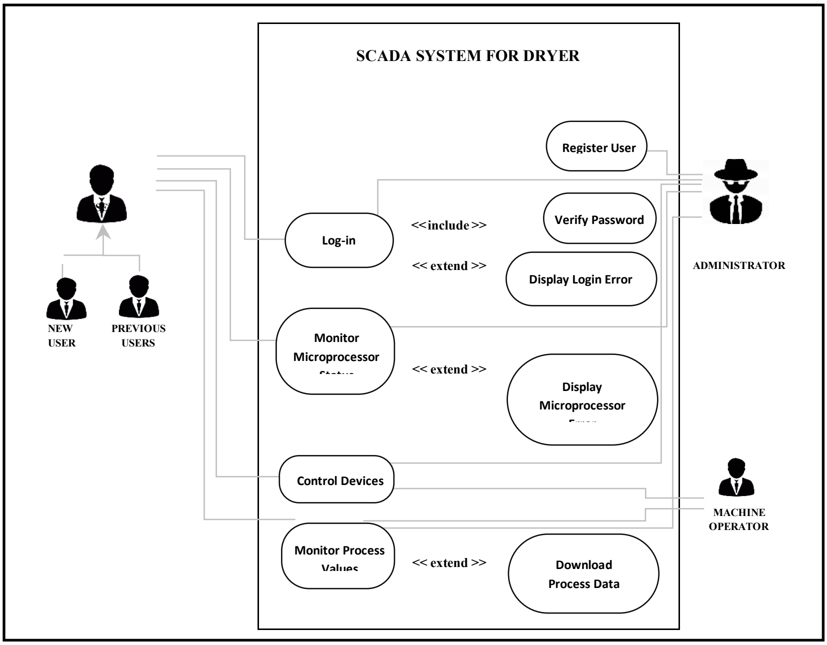


Figure 6. Use-Case Diagram

3.3 Accuracy

To determine the accuracy as a measure of no difference between the sensor and dataset values, specific temperature setpoints were selected based on the 5-point calibration standard (Barua, 2024), such as 28.00°C (0%), 96°C (25%), 164°C (75%), and 300°C (100%). The minimum value of 28°C (0%)

was the normal air temperature where the dryer was not operating. Succeeding values going up to 300°C (100%) was the maximum value the dryer could exhibit. These temperature setpoints were then used as the operational range where the two data values, the sensor value and the dataset, were compared using a paired t-test to determine if these are statistically different. As shown in Figure 7, a box and whisker plot shows the sensor and dataset values across five temperature setpoints. It can be observed that the two plots show almost similar values. This confirms the paired t-test results, where the p-values were 0.048 (one-tailed) and 0.098 (two-tailed), both exceeding the alpha level *(α)* of 0.01, showing no statistically significant difference at a 99% confidence level, which is required for industrial and food-grade applications. This means that the actual sensor readings and the dataset values were not statistically different. Furthermore, this clarifies that the information provided by the web-based SCADA system's downloadable dataset and the actual sensor readings were comparable and accurate.

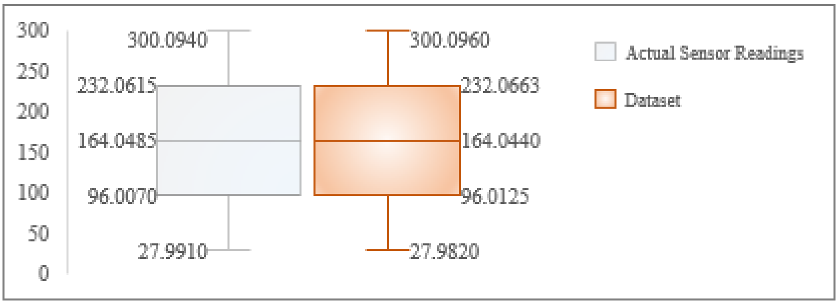


Figure 7. Accuracy Validation of System-Generated Dataset Relative to Sensor Data

3.4 Accessibility

The response time (in milliseconds) measures the interval between when a request is sent by the actors, such as administrators, users, and operators, and when the full response is received by the web-based SCADA. These interactions include button clicks to control specific dryer operations, monitor power values, and download datasets. Based on the mean average response time in Figure 8, it was evident that the system demonstrates *"good"* overall performance, averaging 498.70 milliseconds for end-to-end accessibility across multiple devices. This result was mainly caused by using a local web server, which is located closer to users and data collection points (Glasbergen *et al*., 2020; Ghasemi *et al*., 2020), thereby reducing hardware and distance limitations. On the other hand, a closer look at the standard deviation of 98.44

indicates significant variation when multiple devices interact with the web-based SCADA. Possible causes may include web servers' microprocessor performance, such as CPU (Hadiwandra and Candra, 2021), browser optimization (Antonenko, 2024), RAM (Hasanuddin *et al*., 2020), and the operating system, along with its memory management (Dhuny *et al*., 2022). In addition, the network latency of wireless access points largely depends on signal strength (Bock *et al*., 2021). Furthermore, complexities in the front-end (Lo and Lee, 2023) and backend structure (Odeniran *et al*., 2023) may also contribute.

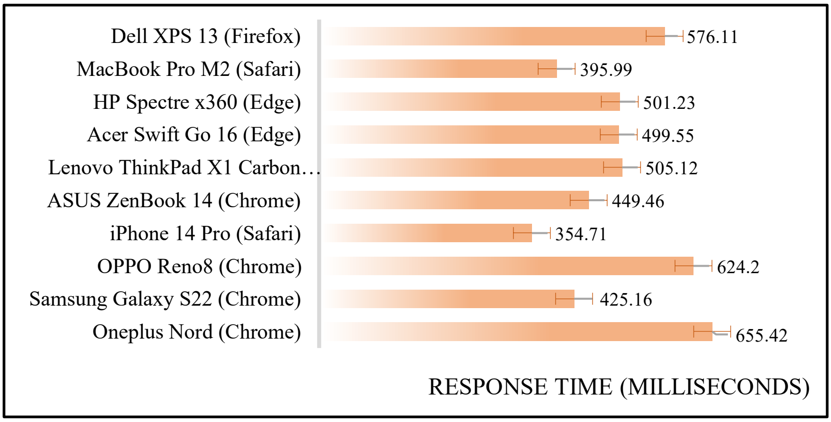


Figure 8. Quantitative Analysis of Device Accessibility Optimization via Mean Average Response Time

3.5 Process Insights

As illustrated in Figure 9, a scatter plot visualizes the trend between the values of InletPV and PowerPV over time. The dataset downloaded from the system showed a noticeable connection between the changes in these process values. The upward trendline initially suggests, the power values were directly influenced by increases in inlet temperature during drying operations.

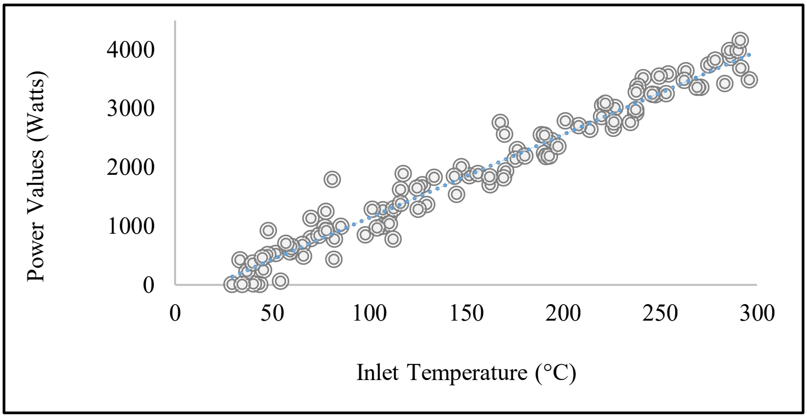


Figure 9. Trend Analysis of Inlet Temperature and Power Consumption

Table 3. Regression Results

Regression Statistics					
Multiple R					0.9776
R Square					0.9558
Adjusted R Square					0.9548
Standard Error					249.30
Observations					100
ANOVA	*df*	*SS*	*MS*	*F*	*Significance- F*
Regression	2	1.3E+08	65122593	1047.808	2.1E-66
Residual	97	6028673	62151.27		
Total	99	1.36E+08			

The multiple linear regression results, as shown in Table 3, established a strong model fit, with an adjusted R^2 value of 0.954, signifying that approximately 95.48% of the changes in the power values can be explained by the dataset available on inlet temperature and time. The overall model was statistically significant, with $F = 1047.81$ and $p < 0.001$. Notably, the inlet temperature was found to be highly significant ($p \approx 1.74 \times 10^{-67}$), linking a strong influence on power values. However, time, as an independent predictor, did not show statistical significance ($p > 0.05$), suggesting it may not be related to changes in power values. The standard error of 249.3 proposes an average prediction error, a negligible variation when compared to the maximum power range of 4000 watts. While these computations show strong descriptive relevance, the findings reflect correlation only, not causation; therefore, further investigation using causal inference techniques was needed to determine actual causal relationships.

4. Conclusion and Recommendation

The study effectively developed a web-enabled SCADA system for an industrial dryer. The system underwent effective testing during trials on a mini-spray dryer capable of 2L production capacity. Some of the system's extra capabilities, such as exhaust, power, blower, needle, and feed rate, may not be compatible with other dryer types with unique functionalities. Performance testing revealed that the system successfully facilitated the downloading of essential datasets. It also showed good interoperability, with response times of $526.33 \pm 20\,ms$ for the login page, $366.33 \pm 8\,ms$ for the control page, $544.67 \pm 32\,ms$ for the heat trend, and an overall latency of 441.21 ± 33 ms. The system was securely designed, integrating authentication, authorization, and password hashing. The system's accuracy was statistically confirmed with p-values of *0.048* (one-tailed) and *0.098* (two-tailed) at a 99% confidence level ($\alpha = 0.01$). Moreover, it also demonstrated good accessibility performance across platforms and browsers, with a mean average response time of *498.7ms*. Furthermore, the process values were well-reflected by the generated dataset, which visually and computationally confirmed with a strong relationship between the inlet temperature and power values (*Adjusted* $R^2 = 0.954$), stressing the need for monitoring power levels within the SCADA system. These findings solidify scalability and practical value for industrial use. As a recommendation, enhanced security features, such as session management and HTTPS encryption, were strongly advised, especially for sensitive environments like pharmaceuticals and military use. For more precise forecasting of power and thermal efficiency, methods such as polynomial regression, time-series regression, and machine learning may also be employed. Overall, the dataset generation provides a basis for superior control, monitoring, and data analysis of industrial drying processes, minimizing dependence on expensive brand-specific hardware and improving user accessibility.

5. Acknowledgement

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