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Process monitoring and control of compost tea production using a PLC–PC based architecture

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ABSTRACT

Ensuring traceability and comparability of process conditions in compost tea production remains a significant engineering challenge in practical applications. Although many studies in the literature primarily focus on the biological and agronomic effects of compost tea, the dynamic behavior of the production process and the time-dependent evolution of key process parameters are often addressed in a limited manner. Rather than aiming to optimize a specific compost tea recipe, this study adopts a process-oriented perspective and proposes the development of a traceable, repeatable, and comparable production infrastructure capable of distinguishing process behaviors under different operating regimes. In this context, a system architecture integrating a PLC-based control layer with a PC-based supervisory monitoring and data acquisition platform was designed and experimentally implemented. Key process parameters, including dissolved oxygen (DO), pH, electrical conductivity (EC), and temperature, were continuously monitored and recorded in a time-stamped manner throughout the production process. The system was evaluated under three experimental scenarios characterized by different aeration and recirculation strategies, while nutrient dosing was kept constant. Time-series analyses of DO, pH, EC, and temperature demonstrated that the proposed PLC–PC based monitoring infrastructure can clearly resolve scenario-dependent process behaviors. The observed differences among experimental scenarios indicate that variations in process dynamics are primarily attributable to operational and control strategies rather than changes in nutrient input. Overall, this study presents an engineering-based framework for process-oriented monitoring of compost tea production, providing a robust data-driven basis for future optimization, advanced control, and scale-up studies.

1. Introduction

The importance of sustainable agricultural production approaches has been increasingly emphasized in recent years due to growing environmental pressures and the long-term adverse effects of chemical inputs (Altieri and Nicholls 2017; Ayla and Altıntaş 2017). In this context, ensuring that agricultural inputs used in crop production are environmentally compatible, traceable, and controllable has become a critical requirement. Organic fertilizers and biological inputs have therefore emerged as prominent alternatives for preserving soil health and reducing the overall burden on ecosystems.

Compost tea is a liquid biological input obtained through the aqueous extraction of organic materials and contains dissolved nutrients as well as diverse microbial communities. The effects of compost tea on plant growth, nutrient uptake, and soil microbial activity have been examined from various perspectives in the literature (Scheuerell and Mahaffee 2004; Ingham 2005). However, in a substantial portion of these studies, the primary focus has been placed on the biological effects of the final product, while the production process itself (specifically, how process conditions evolve over time and how these changes can be monitored) has remained of secondary importance.

In current practice, compost tea production is predominantly based on a single nutrient addition at the onset of the brewing process combined with fixed aeration conditions (Pant et al. 2011; St Martin et al. 2012). Such static production approaches fail to adequately account for the dynamic nature of microbial activity and the time-dependent variation of key process parameters. Moreover, the manual or semi-automated control of production parameters complicates the achievement of comparability between trials and hinders process standardization (Allahyari et al. 2015).

Although the influence of key process parameters on compost tea characteristics has been widely reported (Carballo et al. 2009; Kannangara et al. 2006), continuous time-series-based monitoring remains limited in most studies from an engineering-oriented process control perspective (Lanthier and Peters 2013).

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In biological processes, such as composting and biogas production, continuous monitoring of key operational parameters is a well-established engineering practice used to ensure process stability and consistent performance. In composting systems, this approach typically involves parameters such as temperature and aeration rate (Külcü and Yaldız 2018; Külcü and Yaldız 2005), whereas in biogas production based on anaerobic digestion, parameters including temperature, pH, organic loading rate, and hydraulic retention time are routinely monitored (Drosg 2013; Akman et al. 2014; Yu et al. 2016). In both processes, evaluating process parameters at the time series level constitutes a fundamental approach for understanding process dynamics and comparing different operating regimes (Obileke et al. 2024). Despite these established practices, compost tea production has largely been addressed through static or manually controlled methods, with limited adoption of continuous process monitoring and control strategies, thereby representing a notable gap in the existing literature.

Addressing this gap, the present study evaluates compost tea production from a process design and control perspective rather than from the standpoint of optimizing a specific product formulation. The primary objective of the study is to develop a production infrastructure capable of monitoring process behavior under different aeration, mixing, and nutrient-addition strategies, recording data in a time-stamped manner, and generating comparable datasets across experimental scenarios. To this end, a system architecture integrating a PLC-based control layer with a PC-based supervisory monitoring and data-logging software was designed and experimentally implemented.

The proposed approach addresses compost tea production not as a problem of obtaining the best-performing product, but rather within the framework of understanding and managing the process conditions that shape the final product. In this respect, the study provides an engineering-oriented framework aimed at establishing a process-based data infrastructure required for future optimization, scale-up, and advanced control strategies.

1.1. System architecture

The system architecture proposed in this study was designed to capture the dynamic behavior of the compost tea production process and to enable comparative evaluation under different operating conditions. The architecture consists of a PLC-based control layer responsible for field-level control and a PC-based supervisory software layer providing process monitoring, visualization, and data logging functionalities. This layered structure is consistent with engineering approaches commonly employed in industrial bioprocess monitoring and control.

The PLC-based control layer acquires analog and digital signals from sensors at predefined sampling intervals and operates actuators according to preconfigured experimental scenarios. Within this framework, key process parameters (including temperature, pH, dissolved oxygen (DO), and electrical conductivity (EC)) were continuously monitored, while actuators such as the recirculation pump, blower, and peristaltic pump were automatically controlled. PLC-based control enables deterministic process execution and minimizes operator-induced variability.

The supervisory layer was implemented through a PC-based software platform that communicates with the PLC via standard industrial communication protocols, enabling real-time monitoring and time-stamped data recording. Beyond instantaneous observation, the software supports data archiving and comparison across experimental scenarios, thereby facilitating retrospective process analysis.

A fundamental design principle of the proposed architecture is holistic monitoring of interrelated process parameters along a common time axis. Unlike many compost tea studies that rely on isolated or fragmented measurements, the present system enables a time-series based evaluation of process behavior. Furthermore, the architecture allows flexible implementation of different aeration and mixing strategies through scenario definitions configured in the supervisory software, enabling the assessment of multiple operating regimes on the same physical infrastructure.

Overall, the proposed PLC–PC based architecture treats compost tea production as a traceable, comparable, and repeatable engineering process rather than solely as a product-oriented operation. The developed infrastructure provides a robust platform for future studies focused on process optimization, advanced control strategies, and scale-up applications.

2. Materials and Methods

In this study, experimental investigations were conducted to evaluate the capability of the developed PLC-based control and supervisory monitoring architecture to monitor compost tea production and to distinguish process behavior under different operating conditions. The experimental design emphasizes capturing the time-dependent variation of process parameters rather than improving product quality.

2.1. Reactor configuration and flow arrangement

Compost tea production was conducted in a closed reactor system designed to enable monitoring of biological processes in the liquid phase. The reactor was equipped with auxiliary components supporting aeration, mixing, and nutrient addition, and its internal flow arrangement consisted of a recirculation line, an aeration line, and a nutrient dosing line, as schematically illustrated in Figure 1. Liquid homogeneity was maintained via the recirculation line, with the recirculation pump operated either continuously or periodically according to scenarios defined in the PC-based supervisory software. Oxygen was supplied through the aeration line using a blower with controlled durations and intervals, while nutrient addition was performed using a peristaltic pump with constant dosing timing and duration across all scenarios. Sensor placement within the reactor was selected to ensure representative measurements of overall process behavior, with sensors positioned in regions of stable flow conditions to minimize measurement noise and enhance the reliability of the acquired time-series data.

2.2. Measurement infrastructure and sensors

To ensure traceability of the production process, sensors measuring temperature, pH, dissolved oxygen (DO), and electrical conductivity (EC) were installed within the reactor, as these parameters are widely recognized as key indicators of microbial activity, nutrient concentration, and environmental conditions in compost tea production. Analog signals from the sensors were acquired via the PLC's analog input modules and digitized at predefined sampling intervals, with all measurement data recorded and archived in a time-stamped manner by the supervisory software. The measurement ranges and intended applications of the sensors are summarized in Table 1. Prior to experimental implementation, sensor calibrations were verified

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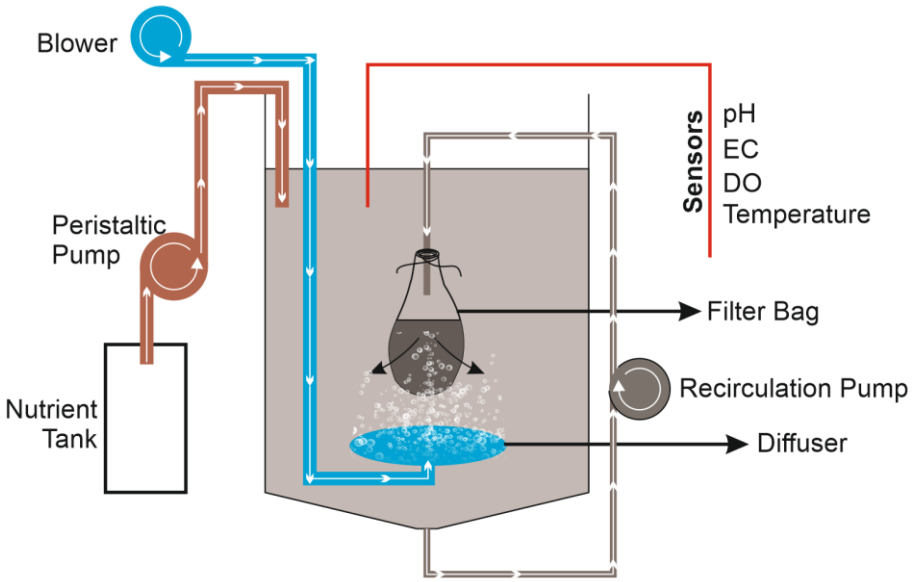


Figure 1. Schematic representation of the reactor used in compost tea production.

Table 1. Sensors and measurement ranges used in the compost tea production system

Sensor Type	Measured Parameter	Measurement Range	Intended Application
Temperature Sensor	Temperature (°C)	0–100	Thermal monitoring of the brewing environment
pH sensor	pH	0–14	Monitoring of microbial activity
DO sensor	Dissolved oxygen (mg L^{-1})	0–20	Assessment of aeration effectiveness
EC sensor	Electrical conductivity (mS cm^{-1})	0–19.9	Monitoring of nutrient concentration

and potential deviations affecting measurement reliability were minimized, with measurement stability during long-term operation considered a critical factor in overall system performance evaluation.

2.3. PLC-based control structure

The control infrastructure of the system was implemented using an industrial-grade PLC compliant with relevant industrial standards. The PLC acquired sensor data at predefined sampling intervals, executed the control logic, and managed actuators according to preconfigured experimental scenarios, enabling deterministic control execution and reducing uncertainties associated with operator intervention. A visual representation of the PLC hardware developed for system control is presented in Figure 2. Within the defined control scenarios, different operating modes were specified for the recirculation pump, blower, and peristaltic pump, with recirculation and aeration treated as the primary control variables influencing process behavior, while nutrient addition was kept constant to ensure that observed differences originated solely from applied control strategies. This configuration was essential for evaluating the sensitivity of the developed system architecture to variations in process conditions.

2.4. Supervisory monitoring and data logging software

Communication between the PLC and the PC was established via the MODBUS communication protocol, which is widely used in industrial automation applications. The PC-based supervisory software, developed using the Python programming language, enabled real-time monitoring, graphical visualization, and time-stamped recording of sensor data. Beyond real-time observation, the software supports data archiving and comparison across experimental runs, allowing retrospective analysis of the production process. This capability allows compost tea production to be treated as an engineering-oriented process rather than a purely operational activity.

2.5. Experimental procedure and experimental scenarios

Experimental investigations were conducted to evaluate the process behavior of the developed system under different operating regimes. Within this framework, three experimental scenarios (ES1, ES2, and ES3) were defined, in which aeration and mixing strategies were applied in different combinations while nutrient addition was maintained at identical timing and dosage across all experiments. Each scenario was conducted over a continuous 72-hour production period to capture both transient and quasi-steady-state process behaviors, as summarized in Table 2. Prior to each experimental run, the reactor was cleaned and sensor calibrations were verified, and throughout the production process all measurement parameters were continuously monitored via the PLC and recorded in a time-stamped manner by the supervisory software. The resulting data enabled comparative evaluation of process behaviors and assessment of the monitoring capability of the developed system architecture, providing an experimental framework focused on process design rather than defining an optimal production condition.

3. Results and Discussion

The performance of the PLC-based control and monitoring infrastructure developed in this study was evaluated based on time series data obtained under different operating regimes. The DO, pH, EC, and temperature parameters measured within the scope of Experimental Scenarios ES1, ES2, and ES3 were analyzed to assess the system's capability to distinguish process behaviors and to present these behaviors in a traceable manner.

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Figure 2. PLC system developed for system control.

Table 2. Implemented experimental scenarios

Experimental Scenario	Recirculation Pump Operation	Blower Operation	Peristaltic Pump Operation
ES1	1 min ON – 1 h OFF	Continuous operation	22 s ON – 1 h OFF
ES2	OFF	2 min ON – 2 min OFF	22 s ON – 1 h OFF
ES3	Continuous operation	OFF	22 s ON – 1 h OFF

The results presented focus on illustrating how process parameters evolve under different control strategies rather than comparing the performance of a specific compost tea production recipe.

3.1. Evaluation of dissolved oxygen time series

The time series of DO values measured under Experimental Scenarios ES1, ES2, and ES3 are presented in Figure 3. In ES1, where continuous aeration was applied, the DO levels stabilized within a higher and more consistent range of approximately 2.5-3.0 mg L^{-1} following a brief transient period. This observation indicates that the continuous operation of the blower effectively ensured oxygen transfer within the reactor. In ES2, in which the blower was operated periodically, the DO values exhibited pronounced fluctuations over time, oscillating around a lower band of approximately 1.5-2.0 mg L^{-1}. These fluctuations directly reflect the applied aeration cycles and demonstrate the sensitivity of the system to the implemented control strategy. In ES3, where the blower was inactive, DO levels decreased rapidly within the first 4-5 hours, approaching values close to 0 mg L^{-1} and indicating a transition toward oxygen-depleted conditions. These results demonstrate that the developed system is capable of clearly distinguishing between different aeration regimes and of monitoring oxygen dynamics at the time series level. The objective here is not to identify an optimal DO level, but rather to render the system's responses to the applied control strategies explicitly observable.

3.2. Analysis of pH behavior under different process regimes

The time series of pH measurements are presented in Figure 4. In ES1 and ES2, pH values remained within a relatively narrow and stable range of approximately 8.7-8.9 throughout the production period, whereas a pronounced downward trend was detected in ES3, where pH decreased from an initial value of about 8.8 to approximately 7.0 by the 24th–30th hour before exhibiting a slight recovery to around 7.2 toward the end of the process. This behavior suggests that microbial processes progress under different regimes depending on the presence or absence of oxygen. In ES3, the observed decrease in pH occurred gradually over the course of the process rather than as an abrupt change, indicating that the developed monitoring infrastructure is capable of capturing in-process variations with high sensitivity. In this study, pH data were not evaluated against a predefined target range but were instead treated as an indicator revealing how process behavior evolves under different control strategies.

3.3. Interpretation of electrical conductivity time series

EC measurements were considered as an indirect parameter reflecting the time-dependent distribution of dissolved substances within the reactor and the effectiveness of mixing. The EC time series corresponding to ES1, ES2, and ES3 are presented in Figure 5. Starting from a comparable initial value of approximately 1 mS cm^{-1} in all scenarios, EC increased steadily over time, reaching the lowest final value of about 2.5 mS cm^{-1} in ES1, an intermediate value of approximately 3.0 mS cm^{-1} in ES2, and the highest value of approximately 3.6 mS cm^{-1} in ES3. In ES3, the most pronounced increasing trend can be associated with the accumulation of dissolved substances under oxygen-depleted conditions. The EC time series demonstrate that the developed system enables the evaluation not only of biological processes but also of engineering-critical aspects such as measurement quality and process homogeneity.

3.4. Evaluation of temperature time series

The time series of temperature measurements recorded under ES1, ES2, and ES3 are presented in Figure 6. The results indicate clear and consistent differences in temperature profiles among the experimental scenarios throughout the 72-hour production period. Starting from a common initial value of approximately 24°C, ES1 and ES2 exhibited relatively stable temperature

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ranges, settling at approximately 18-19°C and 20-21°C, respectively, without abrupt fluctuations. Although slightly higher temperature levels were observed in ES2 compared to ES1, this difference is considered to be associated primarily with the applied aeration regime and related heat removal conditions rather than with recirculation effects. In contrast, ES3 displayed a distinctly elevated temperature profile, rising rapidly during the first hours and reaching a plateau of approximately 45-46°C after the 36th hour, clearly separating it from the other scenarios. This pronounced increase is strongly associated with the continuous operation of the recirculation pump under a closed-loop configuration, in which uninterrupted mechanical energy input combined with limited heat dissipation promotes the accumulation of thermal energy within the reactor. From a process engineering perspective, these findings demonstrate that temperature, although not actively manipulated as a control variable, emerged as a scenario-dependent process parameter influenced by operational conditions.

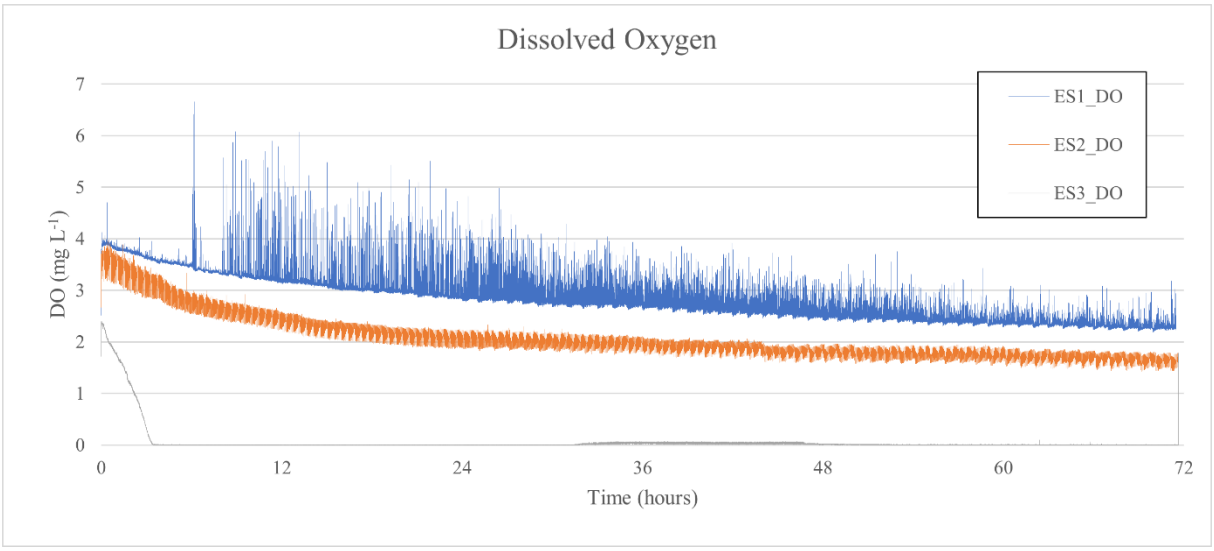


Figure 3. Dissolved oxygen values.

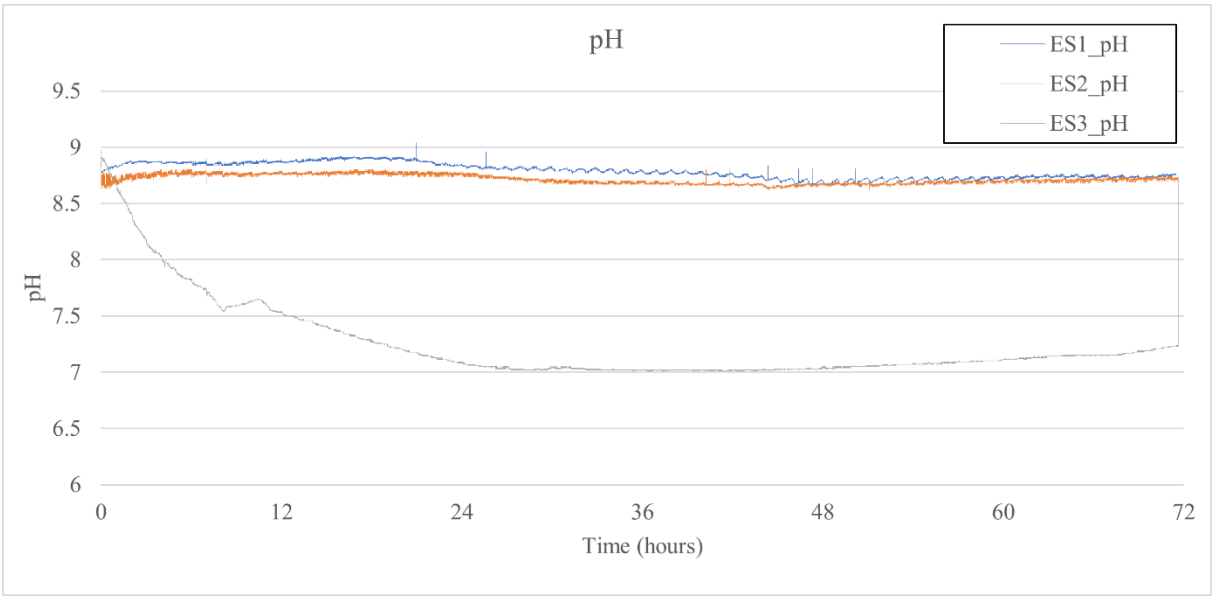


Figure 4. pH values.

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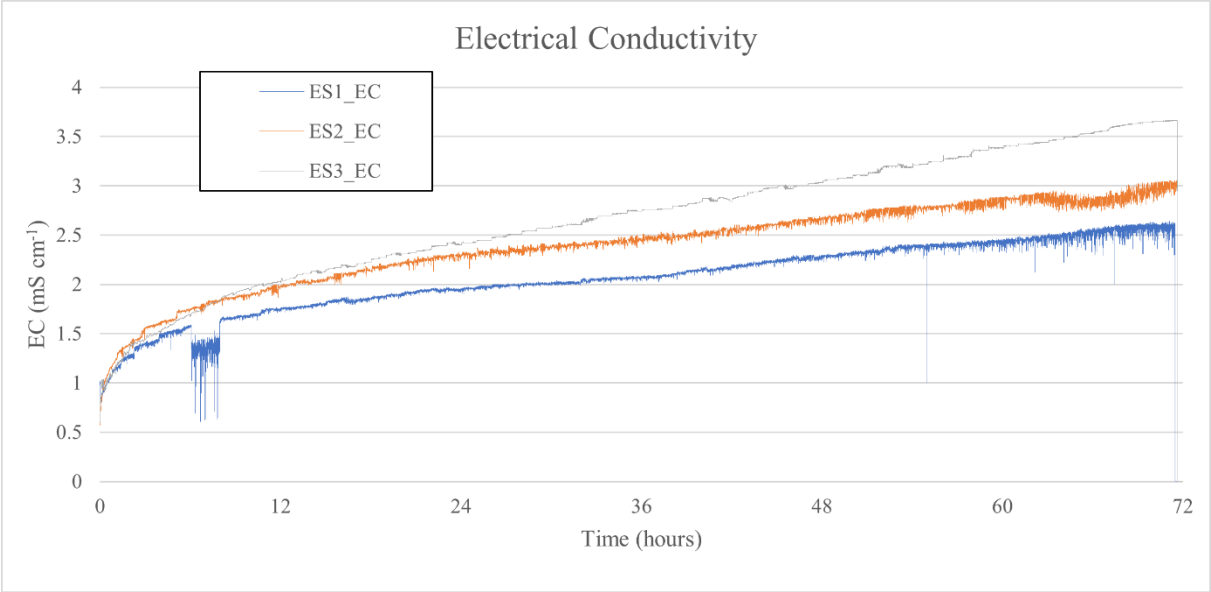


Figure 5. Electrical conductivity values.

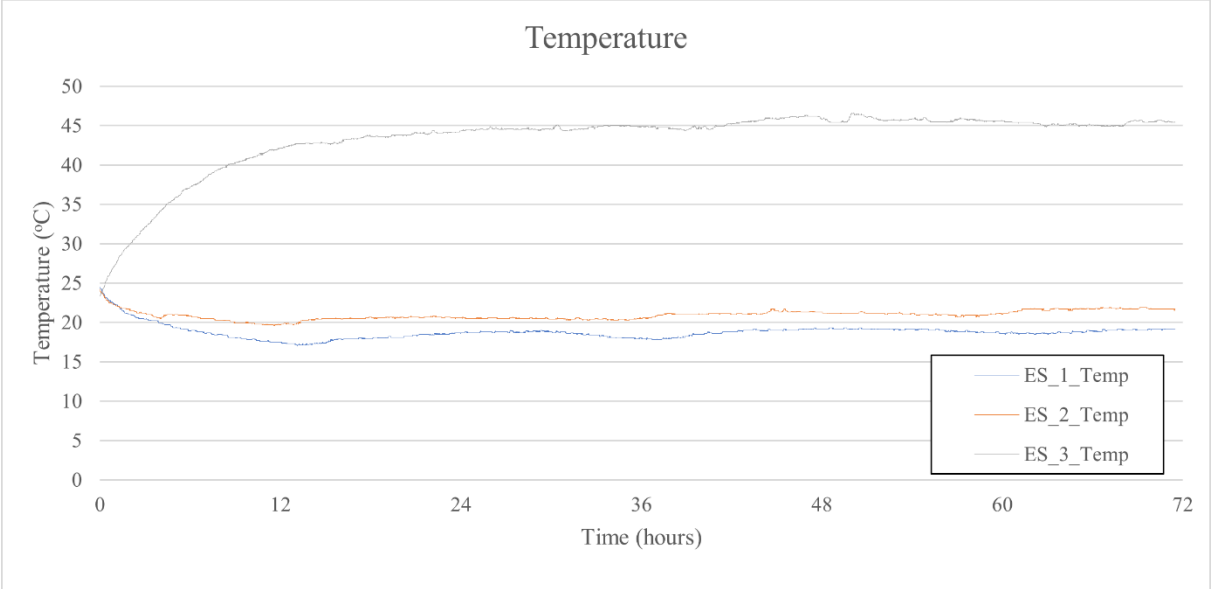


Figure 6. Temperature values.

3.5. Overall assessment

When the time series of DO, pH, EC, and temperature parameters are evaluated collectively, it becomes evident that the developed PLC-based control and monitoring infrastructure can clearly and comparably reveal process behaviors under different operating regimes. The fact that the observed differences among experiments conducted with the same nutrient dosing strategy originated from aeration and mixing strategies confirms that the experimental design was structured in accordance with its intended purpose.

The results presented in this study are not aimed at defining a specific operating condition for compost tea production. Instead, the focus is placed on rendering the effects of different control strategies on process parameters traceable and on evaluating these effects through comparable datasets. In this respect, the findings demonstrate that the developed system architecture provides a viable infrastructure for process design–oriented decision-making.

4. Conclusion

In this study, a PLC-based control and supervisory monitoring infrastructure was developed and experimentally evaluated to enhance the traceability of the compost tea production process and the comparability between experimental runs. The primary objective was not to optimize the performance of a specific compost tea production recipe, but to establish a repeatable, engineering-driven production platform capable of distinguishing process behavior under different operating regimes.

The dissolved oxygen, pH, and electrical conductivity time series obtained from ES1, ES2, and ES3 demonstrate that the developed system can clearly reveal process responses to

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different aeration and mixing strategies. The observation that differences among experiments conducted with identical nutrient dosing strategies originated from control strategies further confirms that the experimental design was appropriately structured for process-oriented evaluation.

The results emphasize the importance of monitoring process parameters at the time series level rather than relying solely on instantaneous measurements in compost tea production. The developed PLC–PC based architecture transforms the production process from an operator-dependent practice into an engineering process that supports retrospective analysis and generates comparable datasets. In this respect, the study contributes to the relatively underexplored process control and monitoring perspective in the compost tea production literature.

In future studies, the proposed infrastructure is planned to be applied to different compost types, variable nutrient dosing strategies, and reactor systems operating at different scales. Furthermore, the evaluation of the acquired time series data using advanced control algorithms, optimization methods, and machine learning–based modeling approaches will enable a more detailed analysis of process performance. Within this context, the presented system constitutes a flexible platform capable of providing the process-based data infrastructure required for product optimization–oriented studies in compost tea production.

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