

Automation In Wet Coffee Processing For Zero Liquid Waste

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ABSTRACT

Wet processing of cherry coffee generates liquid waste with high turbidity and acidity, creating a risk of environmental pollution. This study addresses the need for sustainable technology to achieve zero liquid waste in cherry coffee processing by evaluating the effectiveness of a Programmable Logic Controller (PLC)-based automation system in improving wastewater quality. The system integrates a filtration unit using silica sand and activated carbon with a water circulation mechanism controlled by real-time turbidity and pH sensors. Manual and automatic processes were compared in semi-wash and full-wash modes, with turbidity (NTU) and pH as the primary parameters. Experiments employed real-time sensing, two-way ANOVA, and Tukey HSD analysis. The manual semi-wash process increased turbidity from 0.429 ± 0.015 NTU to 5.219 ± 0.011 NTU and reduced pH from 7.216 ± 0.011 to 6.964 ± 0.022 , while the manual full-wash produced turbidity of 7.811 ± 0.061 NTU and pH of 6.556 ± 0.017 . In contrast, the automatic semi-wash only increased turbidity to 0.467 ± 0.021 NTU, with pH remaining stable at 7.187 ± 0.017 , and the automatic full-wash produced turbidity of 0.470 ± 0.023 NTU and pH of 7.274 ± 0.080 . The automated system also enabled water recycling using turbidity and pH readings, without generating liquid waste. These findings indicate that the proposed technology can reduce water consumption by up to 100% while maintaining process quality and environmental sustainability. This research supports the transformation of the coffee industry toward cleaner and more sustainable practices, particularly in water-limited regions.

Key words: Programmable logic control; water quality; wet processing; water recirculation; turbidity control.

1 INTRODUCTION

Wet processing of coffee fruits, or *the washed method*, is a post-harvest technique used to process coffee fruits into green coffee beans. This process is considered faster than other processes, such as natural and honey, so it is the choice of the coffee industry. This process involves several critical stages, such as *depulping*, fermentation, washing, soaking, drying, and *dehulling*. Each stage significantly influences the quality and final characteristics of the coffee beans (Widodo et al., 2023). Fermentation, for example, is a crucial stage where microbial activity, such as lactic acid bacteria (*Leuconostoc* and *Lactococcus*), shapes the coffee flavour profile. Longer fermentation processes can strengthen the fruit's flavour and acidity, which consumers prefer (Zhang et al., 2019). In addition, wet processing also affects the chemical composition of coffee beans, including the content of sugars, organic acids, and amino acids, which are influenced by microbial activity and fermentation duration (Kleinwächter & Selmar, 2010). Based on the quality of green beans, this process is divided into two stages based on the length of contact with water: semi-wash (8-12 hours) and full-wash (32-36 hours). During the process, this method generates large quantities of liquid waste with high biological oxygen (BOD) and chemical oxygen (COD) requirements, thus requiring proper waste treatment to avoid negative environmental impacts (Rattan et al., 2015).

Liquid waste control of coffee fruits is currently being carried out, and several effective methods have been

developed to overcome this problem, including biological, physicochemical, and sustainable innovation approaches. Biological processes such as *phytoremediation* using plants such as *Phragmites karka* have been shown to reduce total suspended solids (TSS) by up to 95% and colour concentrations by up to 76% (Said et al., 2021). In addition, biofilters with efficient microorganisms and aquatic plants such as *Azolla filiculoides* and *Pistia stratiotes* can reduce BOD by up to 93.4% and COD by up to 94.24%, making treated water suitable for irrigation (Fernanda et al., 2023). Physico-chemical methods such as coagulation and flocculation using ingredients such as ferric chloride or *Moringa oleifera seed extract* are effective in reducing turbidity and colour, while electrocoagulation-electrooxidation (EC-EO) results in total decolourisation as well as a significant reduction in COD (de Araujo et al., 2021). Innovations such as *Microbial Fuel Cells* (MFCs) enable waste treatment while generating electricity, while fertigation utilises treated wastewater for irrigation, providing additional nutrients to plants without damaging the soil.

Although various methods of treating coffee liquid waste have proven effective, each has its drawbacks. *Phytoremediation* requires a large area and a long time, and is influenced by environmental conditions. Biofilters are also susceptible to fluctuations in waste quality and can lose their effectiveness. Physico-chemical methods, such as coagulation, produce residual sludge that requires further handling, while using chemicals can improve the conductivity of treated water.

Electrocoagulation-electrooxidation (EC-EO) requires high investment and energy, making it less economical for large scales. *Microbial Fuel Cells* (MFCs) have low efficiency in COD reduction and are limited to small scales. Fertigation can affect the soil if the quality of the treated waste is not maintained. So, these methods still face challenges related to cost, efficiency, and operational sustainability.

The challenge in wet processing of coffee is how long the soaking time is effective in making water penetrate the mesocarp to the cherry coffee pectin layer. During the process, the water will be contaminated with mucus and dissolved parts during soaking, so this process requires a lot of water, about 40 litres per kg (Agudelo-Escobar et al., 2022).

One of the innovations is to minimise wasted liquid waste by reprocessing water so that water can be used again, and soaking time control is carried out so that the effectiveness of the water used reaches predetermined parameters. Engineering is applied by automating processes using Programmable Logic Control (PLC) technology so that flotation grading, semi-wash, and full-wash are met with their parameters. A previous study by Z (Djafar et al., 2025) researched coffee fruit grading machines that focused on the design and use of tools using charcoal and silica sand's circulation, agitation, and filtration technology. The quality of green beans is obtained by the visual standards of SNI 01-2907-2008 /Indonesian National Standard for semi-wash and full-wash processing, the ability to reduce the turbidity level/turbidity of the semi-wash process from 10.42 NTU to 7.70 NTU according to the domestic waste standard of 5-9 NTU. The quantity of water needed is 306.79 litres per 7 kg of coffee, and raw water in the storage tank can be reused/reused while the water in the main tube is wasted and becomes waste of about 52.55 litres per process (Djafar et al., 2025). However, this study has not addressed the impact of the automation design applied on the volume of water that has the potential to produce zero liquid waste of coffee fruits in main-tubes, so it is interesting and important to discuss. Previously, the machine directly drained water into the main tube without considering its pH and turbidity. Although turbidity is still in the safe range of 7.70 NTU, it is not included in the zero liquid waste category because the raw water used averages 0.47 NTU.

The study focused on the effectiveness of the automation system applied by cherry coffee fruit grading machines in wet treatment, which was directly reviewed against its impact on the liquid waste produced. This study is one of the new insights contributing to the technology of grading coffee cherry fruits, especially in wet processing.

Recent reviews consistently report that wet coffee processing generates effluents with high organic load (COD/BOD), low pH, and intense color/turbidity—posing acute risks to receiving waters if untreated—while also noting that most interventions still concentrate on end-of-pipe treatment rather than process-integrated prevention and reuse strategies

(e.g., advanced coagulation/electrocoagulation, adsorption, biological routes, and membrane systems) (Ijanu, 2020). Field evidence from East Africa (Ethiopia) further documents river quality deterioration downstream of wet mills and highlights the operational constraints of smallholders, strengthening the need for low-complexity monitoring and fit-for-purpose reuse on site (Genanaw 2021; Ulsido 2024). In parallel, circular-economy reviews emphasise valorisation of coffee by-products and water-minimisation as dual levers to cut footprints across the value chain (Tsiggou, 2025; Pongsiriyakul 2024; ICO 2023/24). Against that backdrop, our study contributes to the process side by embedding online turbidity and pH monitoring under PLC control directly into the wet-processing/grading line, targeting source reduction and controlled internal recycling of water—complementary to downstream treatments reported in prior reviews. This responds to calls for practical, automation-ready solutions that are replicable in smallholder contexts while aligning with circular-economy guidance for the coffee sector (Ijanu 2020; Tsiggou, 2025; ICO 2023/24).

Prior field implementation details are documented in Djafar et al. (2025); the present study extends that foundation by embedding real-time turbidity/pH-triggered PLC control to enable closed-loop reuse, thereby positioning the contribution within current state-of-the-art rather than relying on any prospective or unpublished source.

2 MATERIAL AND METHOD

2.1 Machine Design and Manufacturing

The object of this research is the cherry coffee fruit grading machine with the design and unit shown in Figure 1.

This design builds upon a configuration already reported and implemented in field settings at Muntea Village, Bantaeng Regency, South Sulawesi, Indonesia, as published by Djafar et al. (2025), which we adapt here with an integrated PLC-based inline monitoring and closed-loop filtration for zero-liquid-discharge operation. The PLC used is PLC Omron CP1E-E20SDR-A. The working principle of this machine utilizes a pump for backwash circulation, pushing light coffee beans to the surface while separating them from the edges. The machine agitator stirs the coffee beans at the base of the main tube so that the light coffee beans are not crushed and can be pushed upwards to be separated. The filtration system used is silica sand, which functions to remove Total Dissolved Solids (TDS) in water, and activated carbon functions to remove odours, tastes, and colours in water during the semi-wash (8-12 hours) or full-wash (32-36 hours) process. The filtration system uses 50 kg of activated carbon Jacobi brand and 50 kg of silica sand RSA brand (8 mesh). Water quality is monitored automatically using the RK500-07 Type-A turbidity sensor and the RK500-12 Type-C1 pH sensor, both of which

are installed in-line in the main tube. This sensor is directly connected to the PLC, with a turbidity point set at ≥ 0.5 NTU and $\text{pH} < 7$. The circulation pump will continue to run until the sensor detects a turbidity level of < 0.5 NTU and a pH level of > 7 . The main parts of the machine are shown in Figure 5.

The parameters of the engine development are in the automation system that controls valve out 1 and valve out 2 when they should be opened, which is determined by pH and turbidity conditions. The running process conditions the time the coffee fruit comes into contact with water, so the quality parameters are still achieved.

Fresh coffee cherries used in this study were sourced from Bantaeng, South Sulawesi, Indonesia, with the variety Arabica. Before processing, raw water was supplied from local rivers and stored in tanks, along with a variety of Arabica. Prior to processing, raw water was supplied from local rivers and stored in a 500 L HDPE tank. Baseline water parameters were turbidity = 0.43 NTU, $\text{pH} = 7.2$, measured immediately before each batch. All measurements were taken according to the sampling volume and frequency described in Section 2.3. This baseline is used as the reference for “before process” values reported in Table 2.

2.2 PLC Program Design

The design of the machine automation is shown in the block diagram in Figure 2.

The cherry coffee fruit grading machine's automation system is designed to integrate sensor components, controllers, and actuators to achieve wet processing efficiency. System inputs include water quality sensors (turbidity and acidity meters), water level sensors, and flow sensors. Data from the

sensor is processed by a programmed logic controller that regulates the performance of the circulation pump, stirring motor, and output valve. The user interface allows operators to monitor parameters in real-time and adjust if needed.

The program's logic is built to optimise water usage. If the turbidity value exceeds the threshold, the system activates the circulation pump and filters the water through the filtration medium before returning it to the storage tank. The stirring motor works periodically to homogenise the solution while stirring the coffee fruits, while the output valve regulates the discharge of water only if the quality does not meet recycling standards. With this approach, the system can minimise liquid waste while maintaining the quality of the treatment process.

The program is divided into sections shown in Figure 3.

Section_InputSwitch are the logic command for the inputs (PH Sensor, Sensor Level, and Turbidity Sensor). The PLC ladder Section_InputSwitch is shown in Figure 4 below:

Section_Timer0, Section_Timer1, and Section_Timer2 are the operational waiting times of actuators such as pump timers, agitator timers, open/close valve timers, and idle time timers. Meanwhile, Section_OutputAktuator is a logic command for output as an actuator (Valve, pump, and agitator). The PLC Ladder Section_OutputAktuator shown in Figure 5.

2.3 Data Analysis

The test scenario is carried out by comparing the quality of the test mode, namely, manual mode and automatic mode. The conditions that are compared are turbidity and pH sensors in the engine (automatic process) with the absence of turbidity and pH sensors in the machine (manual process). A comparison of conditions is shown in Table 1 and Figure 6.

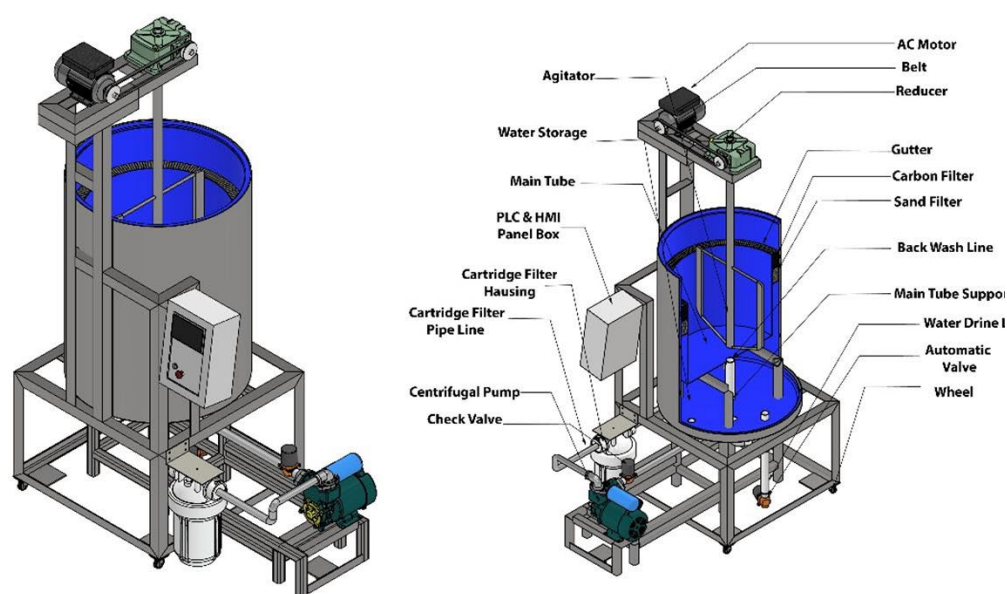


Figure 1: Cherry coffee fruit grading machine design and unit.

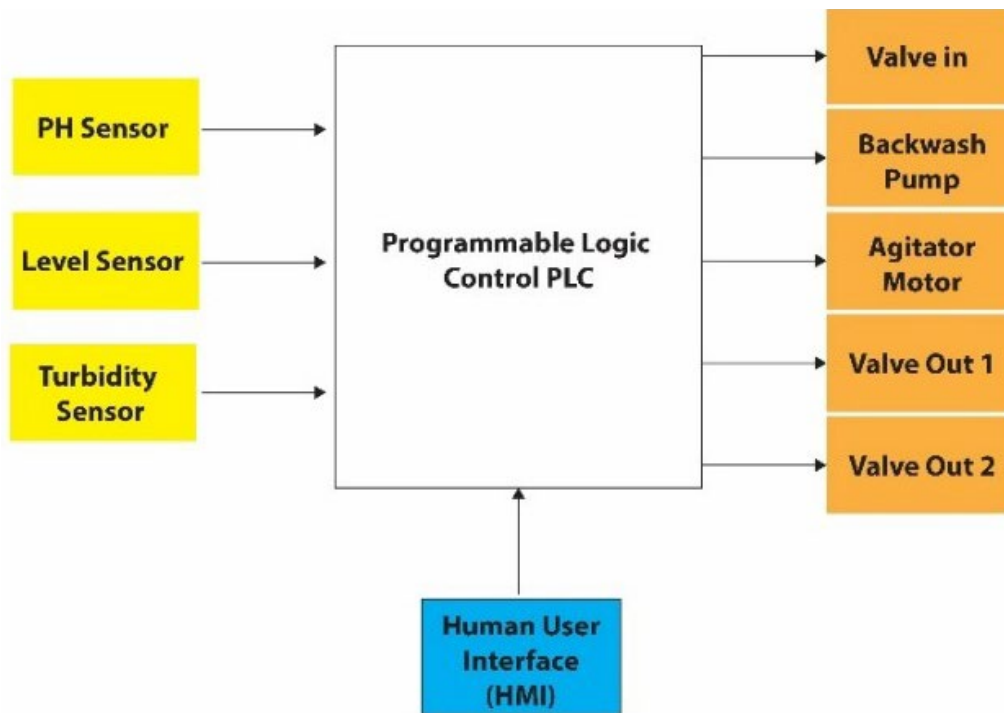


Figure 2: Block diagram of the automation of the cherry coffee fruit grading machine.

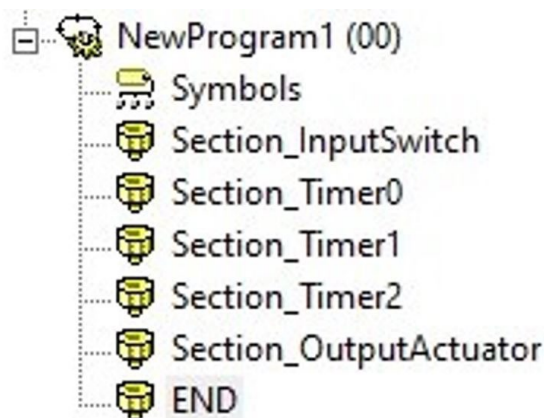


Figure 3: Program section of the coffee cherry grinding machine.

The data was taken based on the machine's working principle, namely, in semi-wash processing and full-wash processing using 7 kg of cherry coffee. For each experimental run, 7 kg of cherry coffee cherries were processed per batch in both manual and automatic modes, keeping the coffee load identical across all treatments. The same batch size was used for semi-wash and full-wash configurations to ensure comparability of turbidity and pH responses. Each batch of completed processes is replaced with a new batch. The water quality samples tested were the pH and turbidity of the water at the sample point storage tank and on the main tube, which is the water drain process at the bottom of the machine. Water samples are taken up to 7 times in manual and automatic mode, as much as 300 ml. Next, the sample is coded with the format

"XXX0Y". XXX stands for the testing process, namely Manual Semi-wash (MSW); Manual Full-wash (MFW); Automatic Semi-wash (ASW); and Automatic Full-wash (AFW). 0Y is the sample sequence number starting from 01 to 07. Sample naming example "AFW02". To test the validity and significance of the data, a two-way ANOVA test and a comparison test with the Tukey HSD method were carried out using Minitab software.

The experiment used a 2×2 factorial with independent replication: Process (Manual vs Automatic) and Wash Type (Semi-Wash vs Full-Wash) factors. Each cell has n = 7 replication, resulting in observations on turbidity (NTU) and pH after the process; before-process (BP) is also recorded for a comparison of the early-late conditions (see Table 1 and the process condition chart).

3 RESULT

The results of the automation test of the cherry coffee fruit grading machine are shown in Table 2.

The test data results showed that the PLC-based automation system managed to maintain water quality significantly compared to manual mode. In the manual semi-wash process, the turbidity value of the water after the process increased from 0.429 ± 0.015 NTU to 5.219 ± 0.011 NTU, while the pH decreased from 7.216 ± 0.011 to 6.964 ± 0.022 . Meanwhile, in semi-wash automatic mode, the turbidity of the water only slightly increased from 0.433 ± 0.021 NTU to 0.467 ± 0.021 NTU with a stable pH from 7.224 ± 0.08 to 7.187 ± 0.017 . A similar pattern is seen in the full-wash

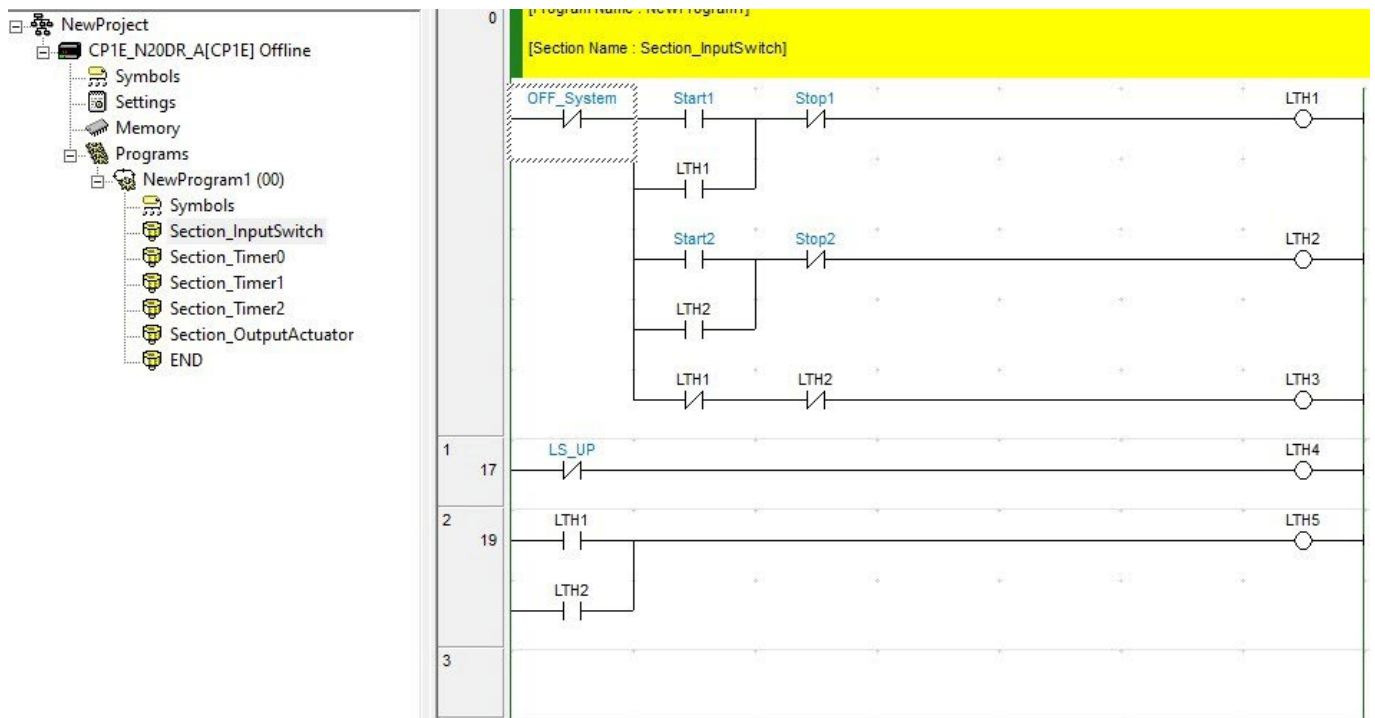


Figure 4: PLC Ladder Section_InputSwitch.

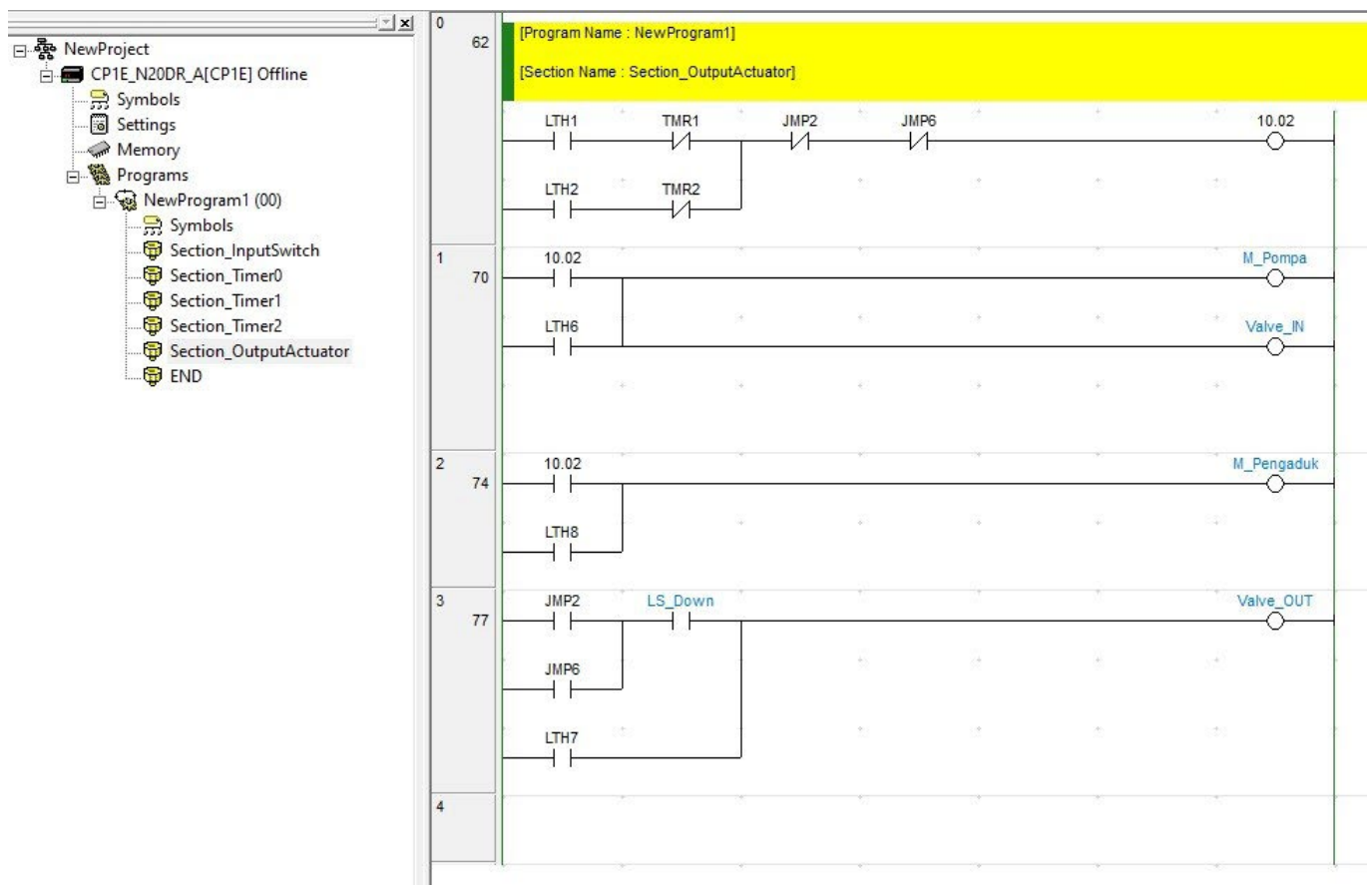


Figure 5: PLC Ladder Section_OutputAktuator.

process, where the manual mode produces turbidity from 0.433 ± 0.013 NTU to 7.811 ± 0.061 NTU and pH from 7.220 ± 0.010 to 6.556 ± 0.017 , while the automatic mode manages to maintain turbidity from 0.430 ± 0.017 to 0.47 ± 0.023 NTU and pH from 7.217 ± 0.011 to 7.274 ± 0.080 . The final quality data of the waste produced (turbidity and pH of water) for each automatic and manual process is shown in Figure 7.

Table 1: Automatic and manual conditions

Aspect	Manual Process	Automatic Process
Process Duration	- Semi-Wash: 8-12 hours - Full-Wash: 32-36 hours	- Semi-Wash: 8-12 hours - Full-Wash: 32-36 hours
Pump & Agitator Control	- Runs 15 minutes every 60 minutes - Idle until next cycle	- Runs 15 minutes every 60 minutes - Final hour: Continuous operation + real-time sensor monitoring (NTU/pH)
Water Quality Monitoring	None	- NTU/pH sensors are active during the final hour - Data triggers circulation/filtration decisions
Post-Process Action	Immediate drainage without checks	- Check NTU/pH: · If $NTU \leq 7$ & $pH \ 6.5-7.5$ → circulate to storage · Else → filter and retest

Figure 7a compares the final results of the turbidity obtained by each automatic and manual process, both semi-wash and full-wash processes. In addition, the comparison of the pH final result is shown in Figure 7b. During the semiwash and complete wash process, changes in the quality of cherry fruit wastewater before and after the process are shown in Figure 8.

This difference indicates that PLC automation effectively controls water circulation and filtration, so the liquid waste generated meets the zero waste criteria. The consistency of turbidity and pH values in automatic mode also indicates the system's reliability in maintaining water quality during treatment. The results of the turbidity data validation are shown in Figure 9:

The results of the two-way statistical analysis of ANOVA in Figure 9 show that the water conditions before and after the cherry coffee grading process have a very noticeable difference. Water quality, especially the turbidity level, changes significantly depending on the treatment method used. Both the water condition factor (before/after the process) and the type of washing process (manual semi-wash, automatic semi-wash, manual full-wash, automatic full-wash) have a significant influence on the final result ($P\text{-Value} < 0.05$).

The interaction between the two factors also shows an interesting pattern. Changes in water turbidity do not

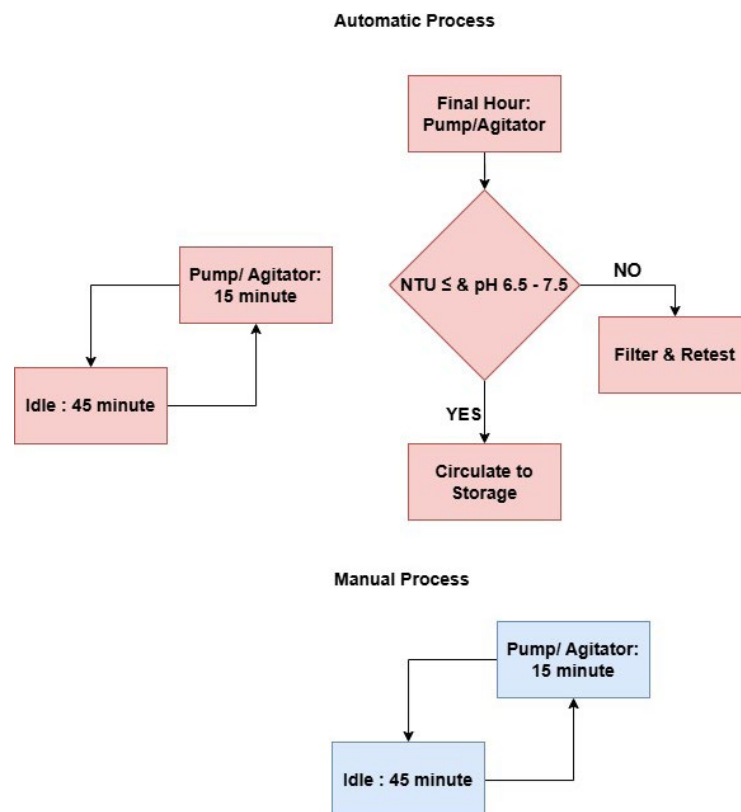
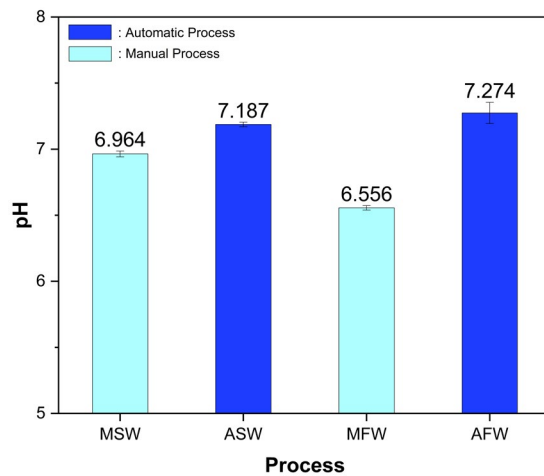
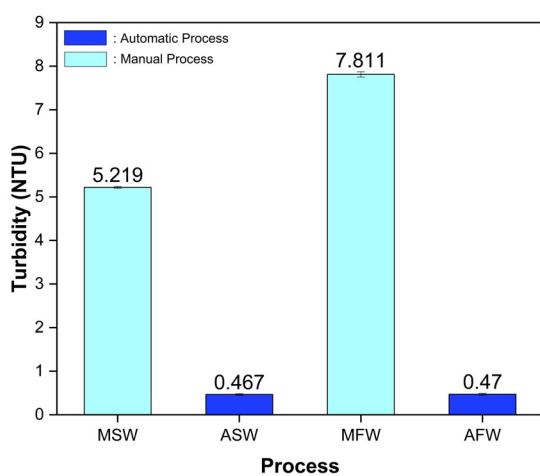


Figure 6: Automatic and manual process condition chart of the cherry coffee fruit grading machine.

Table 2: Turbidity and pH of water samples before and after processing under manual and automated modes.

Water Parameter Before Process				Process	Water Parameter After Process				
Turbidity (NTU)	Turbidity Average (NTU)	pH	pH Average		Sample Code	Turbidity (NTU)	Turbidity Average (NTU)	pH	pH Average
0.43	0.429 ± 0.015	7.21	7.216 ± 0.011	Manual Semi-wash	MSW01	5.21	5.219 ± 0.011	6.98	6.964 ± 0.022
0.42		7.21			MSW02	5.24		6.99	
0.46		7.24			MSW03	5.22		6.96	
0.42		7.21			MSW04	5.21		6.96	
0.42		7.21			MSW05	5.22		6.97	
0.43		7.21			MSW06	5.22		6.92	
0.42		7.22			MSW07	5.21		6.97	
0.44	0.433 ± 0.013	7.22	7.220 ± 0.010	Manual Full-wash	MFW01	7.82	7.811 ± 0.061	6.52	6.556 ± 0.017
0.45		7.21			MFW02	7.68		6.57	
0.42		7.22			MFW03	7.81		6.55	
0.42		7.24			MFW04	7.84		6.56	
0.44		7.21			MFW05	7.85		6.56	
0.44		7.22			MFW06	7.82		6.56	
0.42		7.22			MFW07	7.86		6.57	
0.44	0.433 ± 0.021	7.22	7.224 ± 0.08	Automatic Semi-wash	ASW01	0.46	0.467 ± 0.021	7.18	7.187 ± 0.017
0.41		7.24			ASW02	0.48		7.19	
0.47		7.22			ASW03	0.44		7.21	
0.44		7.23			ASW04	0.48		7.21	
0.42		7.22			ASW05	0.49		7.17	
0.44		7.22			ASW06	0.48		7.17	
0.41		7.22			ASW07	0.44		7.18	
0.42	0.430 ± 0.017	7.21	7.217 ± 0.011	Automatic Full-wash	AFW01	0.45	0.47 ± 0.023	7.44	7.274 ± 0.080
0.44		7.22			AFW02	0.46		7.29	
0.46		7.21			AFW03	0.44		7.21	
0.44		7.24			AFW04	0.48		7.29	
0.42		7.21			AFW05	0.51		7.25	
0.42		7.21			AFW06	0.48		7.23	
0.41		7.22			AFW07	0.47		7.21	

**Figure 7:** a. Turbidity in the automatic and manual process of the cherry coffee fruit grading machine. b. pH in the automatic and manual processes of the cherry coffee fruit grading machine.

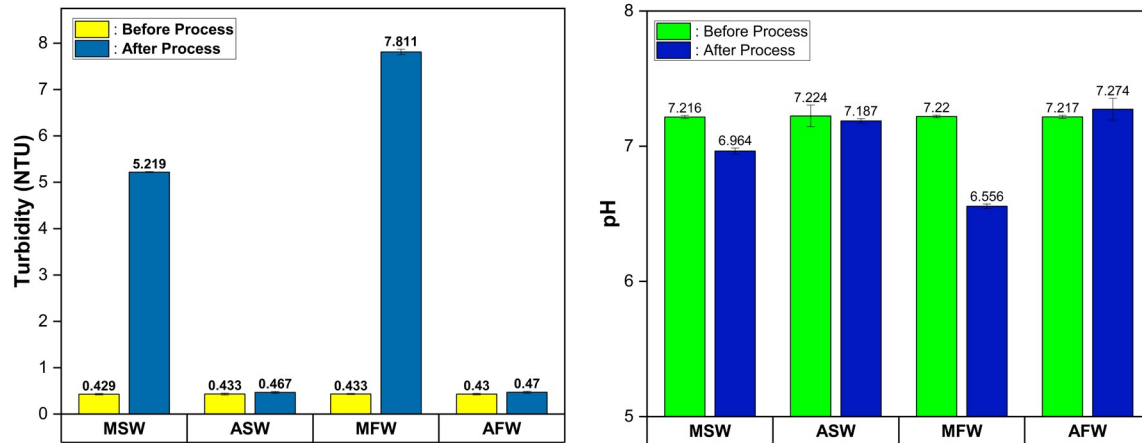


Figure 8: a. Turbidity before and after the cherry coffee grading machine process. b. pH before and after the process of the cherry coffee grading machine

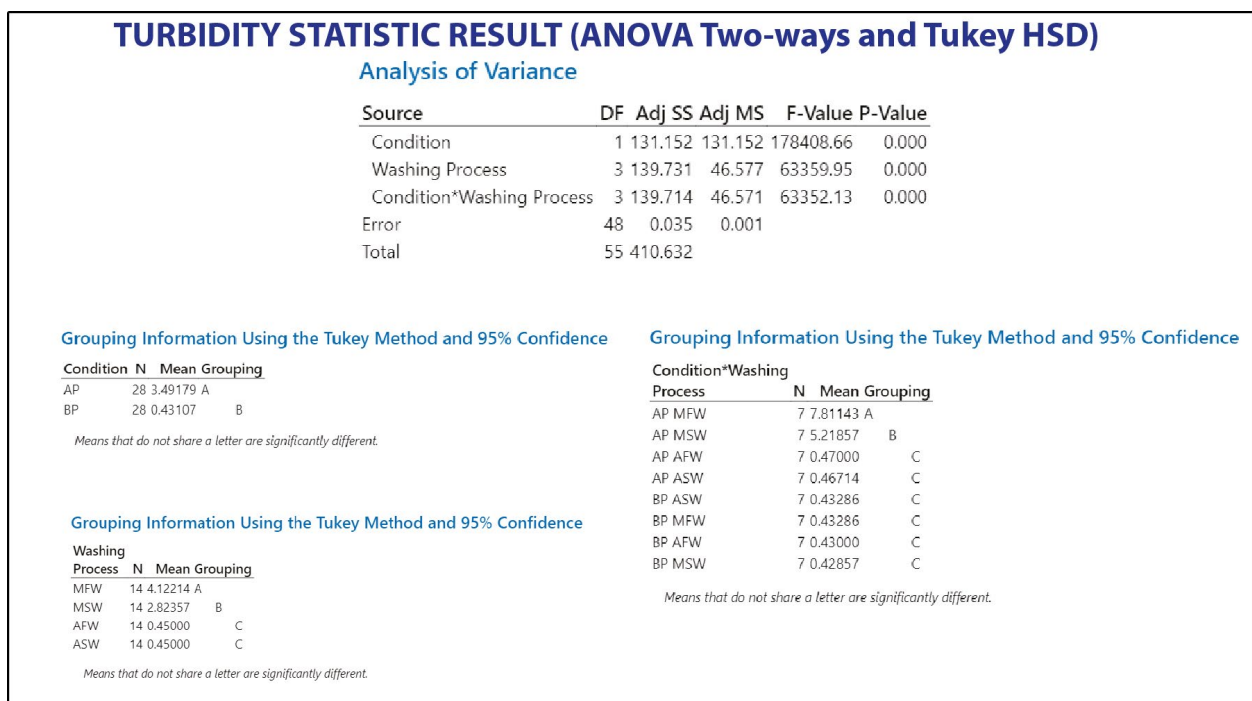


Figure 9: The 2-way ANOVA statistical test results and the Tukey HSD comparison test on the turbidity value.

occur randomly, but instead follow a specific pattern that is influenced by a combination of the initial conditions of the water and the chosen treatment method. This can be seen from how automated systems maintain water quality close to initial conditions, while manual processes cause greater changes. This provides evidence that automated systems with controls affect the final result and how the processing process interacts with water quality. The consistent differences between treatment groups show that the choice of treatment method has real consequences for the quality of the wastewater produced.

The results of the Tukey HSD comparative test in Figure 9 show the process conditions (Before the process-BP

/ After the process-AP) It is divided into two groups which means that the turbidity conditions before the process and after the process there are significant differences. In the washing process (MSW, MFW, ASW, AFW) is divided into three different groups where ASW and AFW are in the same group because the turbidity values are not significantly different while MSW and MFW have their own groups because they have significantly different turbidity values. This indicates that the automatic process is able to maintain turbidity well. This is clarified by the results of the comparison test between the conditions (BP/AP) and the washing process which is divided into three groups where AP MFW has the highest turbidity

value (A) and followed by AP SMW (B). Meanwhile, the group with the lowest turbidity value is in group C, namely AP AFW, AP ASW, BP ASW, BP MFW, BP MSW, and BP AFW. The presence of AP AFW and AP ASW in group C indicates that the turbidity stability after the automatic process is the same as the initial condition before the washing process. The results of the pH data validation are shown in Figure 10 below:

Figure 10 shows significant variations in pH levels based on treatment conditions and methods. Bidirectional ANOVA proves that the processing stage (BP/AP) and the washing method significantly affect the pH value, with a strong interaction effect between the two factors. The Tukey test reveals an apparent clustering, where AFW maintains the highest pH, while MFW produces the lowest pH. Further interaction analysis showed that the automated process was better able to keep the initial pH condition than the manual method, especially seen in the post-process measurements, where the computerised treatment (AFW, ASW) maintained a pH close to neutral while the manual method (MSW, MFW) showed significant acidification.

These findings quantitatively prove that automated processing is more effective in maintaining water quality parameters, supporting its effectiveness in sustainable coffee processing. The clear separation between the averages in Tukey's grouping reinforces the reliability of the observed differences. This statistical evidence strongly supports the application of automated systems for turbidity and pH stability in coffee wet processing operations. The consistency of the automatic method's performance over various washing

durations demonstrates its robustness in maintaining optimal processing conditions, which is critical for product quality and environmental sustainability. The significant pH maintenance on automated systems compared to acidification on manual methods provides clear evidence of the advantages of automated process control technology.

4 DISCUSSION

The results showed that the automation of the PLC-based cherry fruit grading machine managed to maintain water quality significantly, especially in terms of turbidity and pH, compared to manual processes. These findings align with the research of Zhang et al. (2019), which highlights the importance of controlling fermentation parameters in the wet processing of coffee to influence the final quality of coffee beans. Zhang et al. (2019) found that longer fermentation durations can improve coffee's fruit flavour and acidity, but also emphasise the need for effective water management to avoid negative impacts on the environment (Zhang et al., 2019). In this context, the automation applied in this study maintains water quality and allows for repeated use of water, thereby reducing liquid waste.

Research by Djafar et al. (2025) on grading machines with circulation, agitation, and filtration systems has proven that this technology can reduce wastewater but tends to cause an increase in turbidity (7.70 NTU). In addition, their research has not yet achieved zero liquid waste because the water in the main tube is still wasted (Djafar et al., 2025). Innovations made

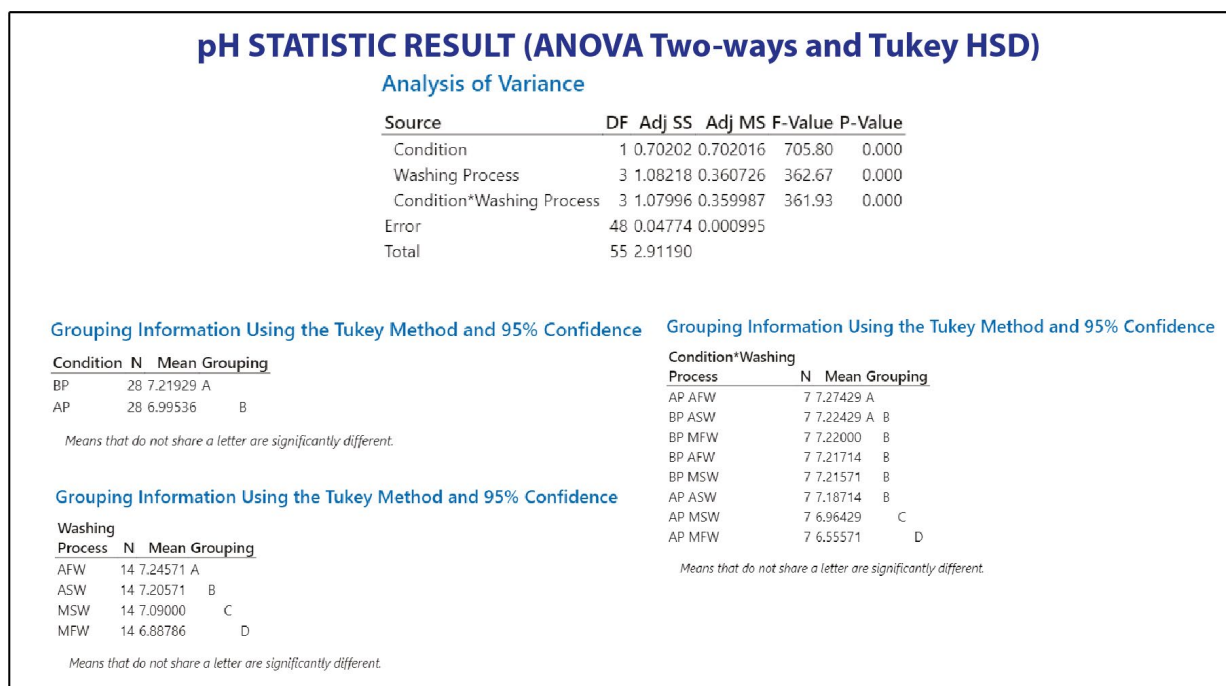


Figure 10: The 2-way ANOVA statistical test results and the Tukey HSD comparison test on the pH value.

by adding sensor-based controls and PLCs have succeeded in overcoming these limitations, so water can be fully recycled without generating liquid waste. This is a step forward in achieving the sustainability of coffee processing, especially in areas with limited water resources. The adoption of PLCs in this study ensures solution homogenization and precise control of immersion time, thereby reducing mucus and dissolved particle contamination—a significant factor causing water quality degradation (Agudelo-Escobar *et al.*, 2022).

In addition, the findings of Rojas *et al.* (2022) on water quality in small-scale coffee production in Amazonas, Peru, reveal that coffee processing wastewater often has a low pH and high turbidity, which can pollute the environment (Rojas *et al.*, 2022). This study proves that automation can mitigate this problem by maintaining neutral pH and low turbidity, so that wastewater meets environmental standards. This is in line with the recommendations of Rojas *et al.* (2022) to apply more efficient technology in small-scale coffee processing.

The combination of findings from the three previous studies and our results shows that integrating automated control, filtration systems, and water recycling is a holistic solution to reduce liquid waste and improve the sustainability of coffee processing. The success of this system also opens up opportunities for broader application, including in areas with limited water resources or strict environmental regulations.

Automating PLC-based grading machines can significantly maintain water quality (turbidity: 0.47 ± 0.023 NTU; pH: 7.274 ± 0.080) and achieve zero liquid waste in wet coffee processing. These findings align with previous studies highlighting the importance of coffee liquid waste management. Ulsido and Li (2016) reported that the coffee wet processing industry produces liquid waste with high BOD/COD (20–60% wet weight) that has the potential to pollute the environment if not managed (Ulsido & Li, 2016). The automation in this study addresses these issues through sensor-based circulation and filtration systems, so that liquid waste can be fully recycled, in contrast to conventional practices that rely on direct disposal or composting (Ulsido & Li, 2016).

In addition, this innovation is in line with the recommendations of Campos *et al.* (2021) and Said *et al.* (2023) on the need for a zero-waste approach in coffee processing (Campos *et al.*, 2021). The automation system reduces the volume of liquid waste and saves water by up to 100%, in contrast to conventional biofilter or coagulation methods that produce residual sludge (Said *et al.*, 2023). This efficiency is even more relevant given the findings of Cortés *et al.* (2020) that untreated coffee liquid waste can lower the pH of river water to 3.76–4.44 and increase turbidity (1814 NTU), threatening aquatic ecosystems (Cortés *et al.*, 2020).

In terms of sustainability, automation also supports the concept of the circular economy by reusing process water, as proposed by Setiawan *et al.* (2025) in the utilisation of

coffee solid waste into biochar (Setiawan *et al.*, 2025). The combination of sensor control and activated charcoal filtration in this study even surpassed the effectiveness of biochar adsorption from coffee grounds (Adsorption capacity: 40–75 mg/g) studied by Zungu *et al.* (2022), as it does not require additional energy for the production of adsorbent materials (Zungu *et al.*, 2022).

Although automation has proven to be effective, its implementation requires a high initial investment in PLCs and sensors, as stated by Laili *et al.* (2022). However, long-term operational costs can be reduced through water savings and prevention of environmental fines (Laili *et al.*, 2022). Future studies need to test the scalability of this system in locations with limited resources, referring to the principle of appropriate technology promoted by Beyene *et al.* (2014) in the context of anaerobic treatment of coffee waste (Beyene *et al.*, 2014). Thus, the automation of coffee grading machines not only answers the technical challenges of liquid waste treatment but also contributes to the SDGs goals related to clean water and sustainable production (Said *et al.*, 2023). Our PLC-based, inline control framework operationalises water-fit-for-use and circularity principles in wet coffee processing and complements end-of-pipe treatments highlighted by recent reviews, particularly for smallholder and East-African-like settings where low-complexity monitoring is decisive (Ijanu 2020; Genanaw 2021; Ulsido *et al.*, 2024; Tsigkou, 2025).

Our results show that PLC-based automation is able to maintain a near-neutral pH and post-process turbidity comparable to the pre-process conditions of the water in AFW/ASW mode, while manual processes result in a noticeable decrease in water quality (turbidity increase & pH decrease). These findings enrich the discussion of studies that rely on post-process phytoremediation/biofilters: these approaches are effective in lowering pollutant loads, but generally still produce residual effluent and/or require longer land and residence times. By putting quality control in-line (pH & NTU sensors as decision triggers), our system prevents water quality degradation from the upstream so that the end-of-pipe requirement is reduced. Thus, automation complements (not replaces) previously reported phytoremediation/biofilter practices (Said *et al.*, 2023; Fernanda *et al.*, 2023), especially in the context of land limitations and the zero-liquid-discharge target.

In practical terms, this PLC-based in-line system still has technical limitations—especially the potential for drift/fouling sensors at turbidity/pH that require periodic cleaning and calibration—as well as the need for media maintenance and the availability of pump/valve parts. From an economic point of view, electricity, media, calibration standards, and labor will determine the payback depending on the local water/energy tariff and the scale of production. For cross-context adoption, we recommend low-cost batch variants (micro-PLC, single transmitter, sand, optional solar) for smallholders, as well as modular skids with

redundancy (parallel pumps/valves, data logging, SCADA integration) for small-scale industries—both of which maintain the same quality control logic. This approach places automation as an upstream prevention that can be combined with simple polishing when raw water quality fluctuates greatly, while maintaining replicability and scale-up readiness.

5 CONCLUSION

This study demonstrates that the PLC-based cherry coffee grading machine successfully achieved zero liquid waste by maintaining process water quality at recyclable levels. In automatic operation, turbidity remained very low, increasing only from 0.433 to 0.467 NTU in semi-wash and from 0.430 to 0.470 NTU in full-wash, while pH stayed near neutral (7.187–7.274). In contrast, manual processing raised turbidity to 7.811 NTU and lowered pH to 6.556, confirming the superior environmental performance of the automated system.

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7 AUTHOR'S CONTRIBUTION

Conceptual Idea: Arminas, M. Massaguni; Methodology Design: Arminas, W. Mudriadi, M.L. Sonjaya; Data Collection: W. Mudriadi, M.F. Azis, M.N.H. Amaluddin; Data Analysis & Interpretation: M. Massaguni, M.L. Sonjaya; Statistical Analysis: M. Massaguni; Writing & Editing: Arminas, W. Mudriadi, M.L. Sonjaya; Supervision: Arminas, M. Massaguni.

8 DATA AVAILABILITY STATEMENT

Data available upon request to authors.

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