

Environmental assessment and efficiency of green technologies applied to the coffee post-harvest process

Claudia Fernanda Ordoñez-Gómez¹, Juan Gonzalo Ardila-Marín¹, Jordan Alexis Castillo-Coronado²

¹ Universidad Surcolombiana, Neiva, Huila, Colombia. E-mail: klaufrog85@gmail.com, juan.ardila@usco.edu.co

² Universidade Federal de Lavras, Lavras, Minas Gerais, Brasil. E-mail: lubey98@hotmail.com

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ABSTRACT

Eco-friendly coffee processing aims to minimize environmental impact, with emphasis on reducing water consumption and wastewater pollution. In this context, this study evaluated the environmental impact and efficiency of two green technologies used in the post-harvest process: Ecoline® (ECL) and Ecowasher® (ECW), implemented on two coffee farms located in the department of Huila, Colombia. The variables analysed included coffee cherry mass, pulping and washing time, water consumption, wastewater volume, processing throughput, percentage of damaged beans, and physicochemical characteristics of the wastewater. The collected data were analysed using descriptive statistics and graphical analyses to compare the repeated measurements obtained under the evaluated operating conditions. Under the evaluated operating conditions, the ECL system demonstrated higher processing throughput (359.7 vs. 316.6 kg h⁻¹ of cherry coffee), whereas the ECW system achieved lower water consumption (0.25 vs. 0.76 L kg⁻¹ of cherry coffee) and a lower percentage of damaged beans (0.60% vs. 0.83%). However, wastewater generated by both technologies did not meet several regulatory discharge limits. These findings suggest that both evaluated processing systems can reduce water consumption compared with conventional wet processing; however, the observed differences should be interpreted within the specific conditions of the two farms evaluated.

Keywords: Wastewater, Eco-friendly post-harvest process, Water consumption, Green technologies.

Avaliação ambiental e eficiência de tecnologias verdes aplicadas ao processo de pós-colheita do café

RESUMO

O processamento ecológico do café tem como objetivo minimizar o impacto ambiental, com ênfase na redução do consumo de água e da poluição gerada pelas águas residuárias. Nesse contexto, este estudo avaliou o impacto ambiental e a eficiência de duas tecnologias verdes utilizadas no processo pós-colheita: Ecoline® (ECL) e Ecowasher® (ECW), implementadas em duas propriedades cafeeiras localizadas no departamento de Huila, Colômbia. As variáveis analisadas incluíram massa de café cereja, tempo de despulpamento e lavagem, consumo de água, volume de águas residuárias, rendimento do processo, porcentagem de grãos danificados e análise físico-química da água residual. Os dados coletados foram analisados por meio de estatística descritiva e análise gráfica para comparar as medições repetidas obtidas nas condições operacionais avaliadas. Nas condições operacionais avaliadas, o sistema ECL apresentou maior rendimento de processamento (359 kg h⁻¹ de café cereja), enquanto o sistema ECW apresentou menor consumo de água (0.25 vs. 0.76 L kg⁻¹ de café cereja) e menor porcentagem de grãos danificados (0.60% vs. 0.83%). No entanto, ambas as tecnologias geraram águas residuárias que excederam os limites de qualidade permitidos. Esses resultados sugerem que os dois sistemas de processamento avaliados podem reduzir o consumo de água em comparação com o processamento úmido convencional; entretanto, as diferenças observadas devem ser interpretadas dentro das condições específicas das duas propriedades avaliadas.

Palavras-chave: Águas residuais, Processo pós-colheita ecológico, Consumo de água, Tecnologias verdes.



1. Introduction

In Colombia, coffee has a significant social, environmental, and economic impact. According to the Colombia Profile of the Ministry of Commerce, Industry and Tourism (MINCIT, 2024), this crop represents approximately 6% of the country's GDP and constitutes its main export product. In addition, it generates employment for more than two million people, mainly in rural areas. Recent sector analyses indicate that Colombia's coffee industry involves more than 550,000 farming families and remains a central pillar of rural livelihoods and national identity (FNC and Minagricultura, 2024). Broader assessments estimate that the sector supports the livelihoods of around 2.5 million Colombians, underscoring its relevance for socioeconomic stability and sustainable development (World Economic Forum, 2025). The high quality of Colombian coffee is attributed to several factors, including the species and variety cultivated, environmental conditions, agronomic management, and processing method (Campuzano-Duque and Wohlgemuth-Blair, 2022).

From an environmental perspective, coffee production can generate positive impacts, particularly through the conservation functions of shade-grown and hillside coffee systems. Coffee plantations can sustain high levels of biodiversity by providing habitat for numerous species of plants, birds, insects, and soil microorganisms, contributing to ecological functions such as pest regulation and nutrient cycling (World Economic Forum, 2025; Ochoa-Henriquez et al., 2024). Additionally, coffee root systems enhance soil stability and reduce erosion, a benefit of particular relevance in Colombian coffee-growing regions where plantations are commonly established on steep slopes (Ovalle-Castiblanco et al., 2022; Rivillas, 2022).

However, this activity may also cause negative environmental impacts, particularly related to water contamination during the coffee processing stage. Studies have shown that the traditional wet-processing method generates wastewater with high organic loads, low pH, elevated nutrient concentrations, and large quantities of suspended solids, posing significant risks to aquatic ecosystems and water quality (Leal-Echeverri and Tobón, 2021; Ijanu et al., 2020). Recent assessments in Colombia have confirmed that coffee mucilage wastewater can reach chemical oxygen demand (COD) values above 25,000 mg L⁻¹, together with high concentrations of total solids and other pollutants, highlighting the need for improved treatment alternatives for small producers (Montes et al., 2023). In response to these challenges, Oliveros and Sanz (2011) and Oliveros-Tascón et al. (2022) reported that the National Coffee Research Center (Cenicafé) developed

several technological innovations aimed at improving production efficiency, promoting responsible resource use, and minimizing environmental impacts. These efforts have led to ecological wet-milling technologies that significantly reduce water use and pollutant loads during pulping and mucilage removal (FNC, 2026). Furthermore, it has been demonstrated that water is not essential in the pulping process; by taking advantage of the natural moisture of the coffee fruit, the seed can be separated from the pulp, reducing by up to 72% the pollution potential generated during this stage (González-Freire and Martínez-Hernández, 2022).

During the 1990s, Cenicafé demonstrated that coffee could be washed and classified using less than 5 L kg⁻¹ of dry parchment coffee (DPC), establishing the technical basis for Colombia's ecological wet-processing systems. Subsequent studies have shown that ecological technologies such as Becolsub® and Ecomill® can further reduce water use and the gray water footprint of coffee processing, in some cases achieving blue water requirements below 1 m³ t⁻¹ and drastically lowering pollutant loads (Leal-Echeverri and Tobón, 2021). These advances align with the broader sustainability efforts of the National Coffee Federation (FNC), whose environmental assessments report significant reductions in water consumption and contaminant discharge achieved through Cenicafé-developed technologies, largely by optimizing by-product handling and minimizing effluents (FNC, 2026). Together, these results reinforce earlier findings that contamination can be reduced by more than 90% when by-products are adequately managed during wet processing (Rodríguez-Valencia et al., 2015), while also highlighting the importance of engineering innovations in mitigating the environmental impacts associated with coffee production (Ijanu et al., 2020).

Coffee processing comprises several stages, including pulping, classification, and transport of the coffee, preferably without the use of water, followed by fermentation in tanks and finally washing using mechanical systems. In Colombia, post-harvest processing is mainly carried out using three approaches: the conventional or wet method, ecological processing with wastewater discharge, and ecological processing without discharge.

The conventional method corresponds to the traditional process used to transform the coffee fruit into seed and is characterized by intensive water use during the pulping, transport, and washing stages. This system can reach water consumption levels close to 40 L kg⁻¹ of DPC and generally does not include adequate management of by-products such as pulp and mucilage (González-Freire and Martínez-Hernández, 2022; Hernández-García, 2024).

In contrast, ecological processing eliminates unnecessary stages through the use of mechanical washers or fermentation tanks and incorporates the management of pulp, mucilage, and wastewater in order to develop an environmentally sustainable process with reduced generation of contaminant discharges. This system uses mechanical washing that can consume less than 0.5 L kg⁻¹ of DPC (González-Freire and Martínez-Hernández, 2022). Additionally, wet processing has a significant impact on the quality of dry parchment coffee, since approximately 80% of the defects present in the beans originate during this stage, highlighting the importance of implementing techniques that reduce contamination without compromising the quality of the final product (Aristizábal and Duque, 2005).

Several studies have evaluated post-harvest practices in coffee production systems. In an analysis of good practices on coffee farms in the municipality of Viotá (Cundinamarca), processing methods were characterized, and the main stages of the process were identified. The results showed that many producers did not perform regular maintenance on their pulping machines, which could generate mechanical damage to the beans. Likewise, some producers were found to use water volumes higher than necessary and lacked wastewater treatment systems (Giraldo-Quintero et al., 2017).

Similarly, in a study conducted in the rural area of La Morena in the municipality of La Plata (Huila), 29 coffee farms were analyzed to evaluate crop establishment, processing methods, and the management of residues generated during pulping (Fernández-Cortés et al., 2020). These results highlight the need to strengthen sustainable production practices

to reduce water pollution associated with residues from coffee processing.

In this context, the present study aims to compare the operational performance and environmental indicators associated with two wet coffee processing systems, from the harvesting of coffee cherries (CC) to the production of dry parchment coffee (DPC). For this purpose, variables such as coffee mass, water consumption, processing time, number of damaged beans, and wastewater volume were measured, and the physicochemical characteristics of the wastewater were evaluated on two coffee farms in the department of Huila, Colombia.

2. Material and Methods

The study was conducted on two coffee farms located in the department of Huila, Colombia. The first farm, La Esperanza, is located in the Lourdes rural district of the municipality of La Argentina (Figure 1). It covers an area of 1 ha and has approximately 3,800 coffee plants. Its geographic coordinates are 2°10'25" N and 76°02'07" W. The area has a warm and humid climate, with an average annual rainfall of 2,500 mm, an average temperature of 20 °C, relative humidity of approximately 80%, and an altitude of 1,730 m above sea level.

The second farm, El Mirador, is located in the Palmito rural district in the municipality of Timaná, in the department of Huila. It has an area of 1 ha and approximately 5,100 coffee plants. Its geographic coordinates are 1°52'41.5" N, 75°58'22.6" W. Climatic conditions are also warm and humid, with an average annual rainfall of 2,800 mm, an average temperature of 24 °C, relative humidity of 85%, and an altitude of 1,567 m above sea level.

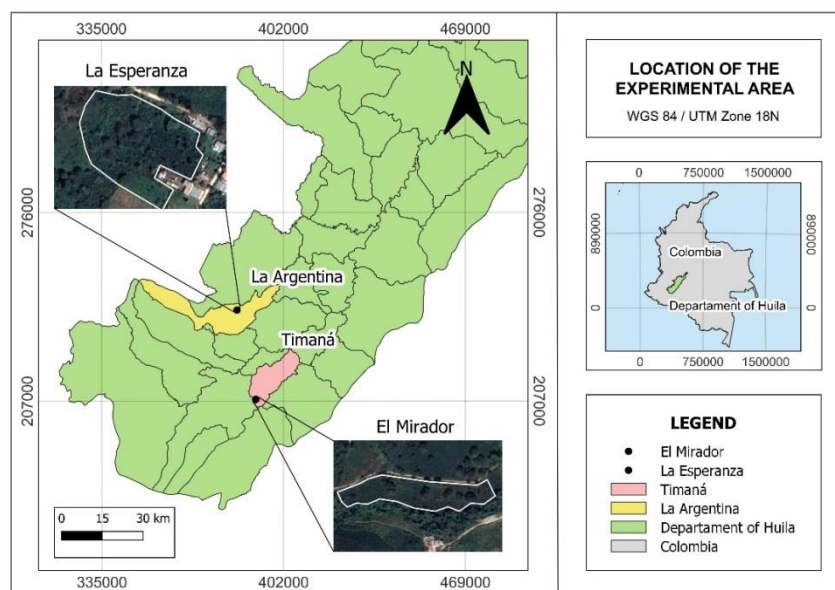


Figure 1. Detailed description of the study region and the sampling area for coffee cherry (CC) samples.

In terms of plant material, the two farms cultivate different coffee varieties. La Esperanza farm grows F6, Catimor, and Colombia varieties, while El Mirador farm cultivates Castillo, Colombia, and F6 varieties. These varietal differences are relevant because they may influence fruit characteristics such as size, mucilage content, and mechanical resistance, which in turn can affect the performance of the processing technologies evaluated.

The sample size (M) was determined based on daily coffee harvest records from the past three years for both farms. The average of the minimum reported values was calculated, establishing a sample size of $M = 290$ kg of coffee cherry (CC) for evaluating the implemented technologies. In this context, two coffee processing systems implemented on different coffee farms were evaluated under their respective operating conditions.

Processing System 1 (PS1), implemented at La Esperanza farm, consisted of a single-stage process integrating pulping, parchment separation, and washing using Ecoline® (ECL) technology. In contrast, Processing System 2 (PS2), applied at El Mirador farm, included pulping and parchment separation in a first stage, followed by a 24-h fermentation period and, finally, washing in a second stage using Ecowasher®

(ECW) technology. Both technologies are manufactured by Penagos.

The evaluated variables included processing throughput (kg min^{-1} of CC) and water consumption (L kg^{-1} of CC), considering specific water consumption (SWC) and the estimation of the Water Management Index in Wet Coffee Processing (WMIWCP). Ten replicate measurements were collected for each processing system for water consumption, processing throughput, and damaged beans, while five repeated measurements were obtained for wastewater volume. Additionally, 10 samples of 1 kg of processed coffee per processing system were collected to determine the percentage of mechanical damage to the beans (%Bd).

Furthermore, the volume of wastewater generated (L kg^{-1} of CC) was quantified with five repeated measurements per farm, as presented in Table 1. Subsequently, a physicochemical analysis of the wastewater was conducted, evaluating the following parameters: Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), fats and oils, pH, settleable solids (SS), and total suspended solids (TSS). These parameters were selected according to the criteria established in Resolution 631 of 2015, in order to determine the level of water contamination and the potential need for treatment (Resolución 631, 2015).

Table 1. Measurement scheme: variables, processing systems, measurement units, number of repeated measurements, and measurement methods.

Variable	Processing system	Measurement Unit.	Number repeated measurements	of Measurement Method
Water consumption kg^{-1} of CC)	PS1	290 kg of CC harvested in the day	10	Flow meter
	PS2	290 kg of CC harvested in the day	10	Flow meter
Output (kg min^{-1}) of CC)	PS1	290 kg of CC harvested in the day	10	Stopwatch and scale
	PS2	290 kg of CC harvested in the day	10	Stopwatch and scale
Damaged bean (%)	PS1	1 kg of washed coffee	10	Scale
	PS2	1 kg of washed coffee	10	Scale
Wastewater volume kg^{-1} of CC)	PS1	20 kg of CC	5	Graduated buckets
	PS2	20 kg of CC	5	Graduated buckets

The yield (y) for PS1 was determined with respect to the time taken to process the sample size (M) of CC using Equation (1), based on the initially measured mass and time.

$$y_{T1} = \frac{Mc}{T} \quad (1)$$

Where: Mc – mass of the coffee cherries (kg); T – coffee processing time (min).

Next, Equation (2) shows the yield for PS2 based on the sum of the times for each stage.

$$y_{T2} = \frac{Mc}{t_1 + t_2} \quad (2)$$

Where: Mc – mass of CC (kg); t_1 – time for pulping and bean separation (min); t_2 – washing time.

Likewise, water consumption (WC) was calculated by expressing the ratio between the volume of water used and the mass of coffee cherries harvested during the day, as shown in Equation (3):

$$WC = \frac{V}{Mc} \quad (3)$$

Where: V – volume of water used (L); Mc – mass of the CC (kg).

Meanwhile, specific water consumption (SWC) was calculated from WC and the conversion factor (F) used to convert coffee cherry (CC) mass to dry parchment coffee (DPC) mass. A value of $F = 5$ was used, based on the recommendations of Marín-López et al. (2003) and Montilla-Pérez et al. (2008), as shown in Equation (4).

$$\text{SWC} = \text{WC} * F \quad (4)$$

On the other hand, the Water Management Index in Wet Coffee Processing (WMIWCP) was calculated by the relationship between the SWC and the maximum water consumption calculated for the conventional method, according to Rodríguez-Valencia et al. (2015), as shown in Equation (5):

$$\text{WMIWCP} = 1 - \left(\frac{\text{SWC}}{4} \right) \quad (5)$$

Meanwhile, %Bd (percentage of damaged beans) was calculated by expressing the ratio between the mass of damaged beans and the total weight of the sample, as indicated in Equation (6):

$$\% \text{Bd} = \frac{M_{\text{Gd}}}{1000 \text{ gr}} * 100\% \quad (6)$$

Where: M_{Gd} – mass of the damaged beans (g)

Finally, to determine the volume of wastewater (WR), 20 kg samples of CC were processed using the corresponding processing method. At the end of the process, the volume of wastewater generated by kg of CC was measured using graduated buckets, as indicated in Equation (7).

$$\text{WR} = \frac{V_r}{20 \text{ kg}} \quad (7)$$

Where: V_r – volume of wastewater (L).

For the physicochemical analysis, a 2 L wastewater sample was collected from each processing system immediately after the processing stage and transported to the laboratory for analysis. The following determinations were performed: Biochemical oxygen demand over 5 days (BOD_5) was determined using Standard Method 5210B, and chemical oxygen demand (COD) was determined using the Standard Method 5220

D method, modified through solvent extraction followed by gravimetric or infrared quantification.

The pH was measured using a calibrated potentiometer following the SM 4500-H⁺ B method; settleable solids (SS) were determined by sedimentation in an Imhoff cone according to SM 2540 F; and total suspended solids (TSS) were quantified by filtration and gravimetric determination following SM 2540 D (APHA, AWWA & WEF, 2017).

Finally, water consumption, processing throughput, and percentage of damaged beans were recorded for each processing system. Descriptive statistics and graphical analyses were used to compare the repeated measurements obtained under the evaluated operating conditions. Because the two processing systems were implemented on different coffee farms, the analysis was intended to describe observed differences rather than to support inferential comparisons between technologies. Microsoft Office Excel® was used to perform the statistical analyses.

3. Results and Discussion

The results obtained under the evaluated operating conditions are presented below.

When analyzing the processing systems, Table 2 shows that PS1 achieved a yield of 359.72 kg of CC h⁻¹, with an average of 5.99 kg of CC min⁻¹. In comparison, PS2 presented a yield of 316.62 kg of CC h⁻¹ and an average of 5.27 kg of CC min⁻¹. The results showed standard errors of 0.05 and 0.01, and coefficients of variation of 2.61% and 0.73% for PS1 and PS2, respectively.

Table 2. Processing time and coffee processing throughput for PS1 (ECL) and PS2 (ECW).

PS1		PS2		
Processing T (min)	Performance (kg min ⁻¹)	Processing t ₁ (min)	Processing t ₂ (min)	Performance (kg min ⁻¹)
49.57	5.85	44.60	9.81	5.33
48.82	5.94	43.88	10.53	5.33
48.33	6.00	44.39	10.95	5.24
48.17	6.02	44.94	9.99	5.28
48.58	5.97	43.78	11.67	5.23
48.74	5.95	44.85	9.97	5.29
48.99	5.92	44.49	10.23	5.30
48.90	5.93	44.46	10.46	5.28
48.74	5.95	44.02	11.01	5.27
45.17	6.42	45.54	10.02	5.22
Average	5.99			5.27

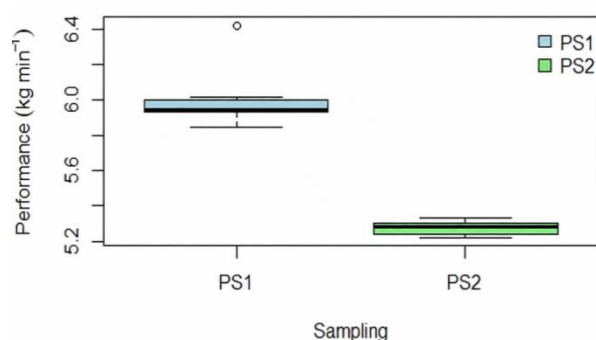


Figure 2. Coffee processing throughput (kg min^{-1}) for PS1 (ECL) and PS2 (ECW).

Based on the results obtained, the ECL technology performed slightly below its optimal processing capacity (400 to $450 \text{ kg of CC h}^{-1}$) (Penagos, 2019a). Several factors could have influenced the results, among them the quality of the cherry coffee. Low selectivity in manual harvesting, which involves picking unripe fruits, can hinder coffee processing. When the cherries are not fully ripe, they are more prone to mechanical damage and often have dry pulp and mucilage adhered to the parchment, which may reduce the machine's efficiency (Fajardo-Peña and Sanz-Urbe, 2003). Maintenance and operation of the machine are other key factors that can affect its performance, as improper maintenance or operation can prevent the machine from reaching its full capacity. These performance levels are consistent with national evaluations of ecological wet-processing technologies, where modern systems such as Becolsub® and Ecomill® have demonstrated stable throughput and improved operational efficiency in Colombian coffee farms (FNC, 2026).

On the other hand, the ECW technology, which, according to its specifications, processes between 300 and $350 \text{ kg of CC h}^{-1}$, performed in line with those expectations. However, it is also important to consider other factors such as cost, ease of use, and maintenance (Penagos, 2019b).

Figure 2 shows the processing performance recorded for PS1 and PS2 under the evaluated operating conditions. The average processing throughput recorded for PS1 was 13.61% higher than that observed for PS2.

Table 3 presents the results for water consumption by the evaluated technologies. For PS1, the average water consumption was 0.76 L kg^{-1} of CC, with a standard deviation of 0.120 L kg^{-1} and a standard error

of 0.038 L kg^{-1} . The coefficient of variation was 15.8% , indicating moderate relative dispersion. The minimum and maximum values recorded were 0.52 and 0.88 L kg^{-1} of CC, respectively, with a range of 0.36 L kg^{-1} of CC, suggesting a normal distribution of the data.

In the case of PS2, average water consumption was 0.254 L kg^{-1} of CC, with a standard deviation of 0.021 L kg^{-1} and a standard error of approximately 0.007 L kg^{-1} . The coefficient of variation was 8.19% . The minimum and maximum values were 0.237 and 0.299 L kg^{-1} of CC, respectively, corresponding to a range of 0.062 L kg^{-1} of CC, which also suggests an approximately normal distribution. The substantially lower specific water consumption observed for PS2 can be interpreted in light of the operational configuration of the evaluated processing system. Unlike PS1, PS2 separates the fermentation and washing stages, allowing mucilage degradation to occur before the final washing step. As a result, less water is required to detach the remaining mucilage from the beans, reducing the overall water demand without compromising the completion of the wet-processing sequence. Previous studies have similarly reported that ecological wet-processing systems incorporating controlled fermentation and optimized washing operations can substantially decrease water consumption while maintaining processing efficiency (Aristizábal and Duque, 2005; Hernández-García, 2024; ECOM Agroindustrial Corp, 2023). Nevertheless, because the present comparison involved two processing systems operating under different farm conditions, this interpretation should be regarded as a plausible operational explanation rather than direct evidence of causality.

Table 3. Total water consumption and water consumption per unit mass of coffee cherry (CC) for PS1 (ECL) and PS2 (ECW).

PS1		PS2	
Water consumption (L)	Water consumption (L kg^{-1} CC)	Water consumption (L)	Water consumption (L kg^{-1} CC)
228.96	0.790	71.39	0.246
216.83	0.748	71.80	0.248
255.90	0.882	71.39	0.246
251.69	0.868	68.64	0.237
250.24	0.863	71.96	0.248

243.69	0.840	86.57	0.299
225.97	0.779	82.86	0.286
195.52	0.674	71.39	0.246
179.66	0.620	69.88	0.241
150.66	0.520	70.34	0.243
Average	0.758	Average	0.254

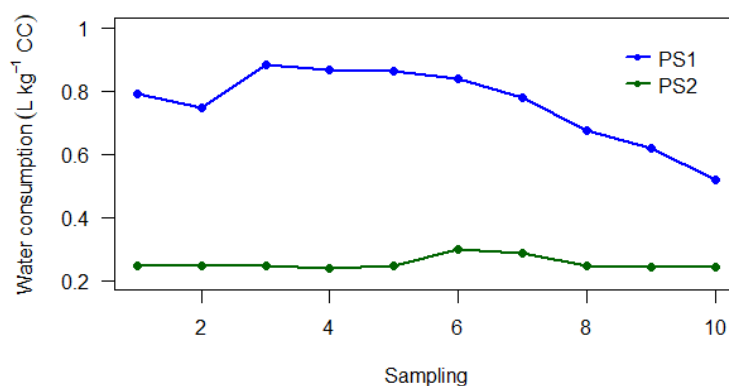


Figure 3. Water consumption per unit mass of coffee cherry ($\text{L kg}^{-1} \text{CC}$) for PS1 (ECL) and PS2 (ECW).

Figure 3 shows that PS1 had an average water consumption of 0.76 L kg^{-1} of cherry coffee (CC), a value that is higher than the consumption specified in the ECL technology datasheet (0.2 L kg^{-1} of CC) by 73.6%. It is important to highlight that, after adjusting the main water inlet, an 11.9% reduction in consumption was achieved during the last two samplings compared to the overall average recorded for PS1. Meanwhile, PS2 recorded an average consumption of 0.25 L kg^{-1} of CC, representing a 96.9% reduction compared to the reference value provided by the manufacturer for the ECW technology (0.5 L kg^{-1} of CC) (Penagos, 2019a; Penagos, 2019b). Similar reductions in water use have been documented in Colombia, where ecological wet-processing systems such as Becolsub® and Ecomill® have reduced the blue water footprint to values below $1 \text{ m}^3 \text{ t}^{-1}$ of processed coffee, confirming the substantial gains in efficiency obtained when water-saving technologies are adopted (Leal-Echeverri and Tobón, 2021).

Figure 3 illustrates the difference in water consumption observed between PS1 and PS2 under the evaluated operating conditions. On average, PS2 required approximately 0.5 L less water per kilogram of processed cherry coffee than PS1, whereas the average water consumption recorded for PS1 was 198.7% higher than that observed for PS2. These findings align with recent sustainability programs in Colombia, where the implementation of water-efficient wet mills has led to reductions of up to 77% in on-farm water use during coffee washing (ECOM, 2023).

According to Rodríguez-Valencia et al. (2015), evaluating the efficiency of a coffee processing technology requires quantifying the specific water consumption and determining its savings and use through the Water Management Index in Wet Coffee

Processing (WMIWCP). This indicator ranges from 0 to 1, where values above 0.75 reflect sustainable water-use practices, while values near 0 indicate consumption levels comparable to the conventional wet-processing method, which typically requires more than 40 L kg^{-1} of dry parchment coffee (DPC). Scientific reports on coffee wet processing describe the traditional method as highly water-intensive, with substantial volumes required for pulping, transport, and washing operations, thereby exerting significant pressure on surface water sources (González-Freire and Martínez-Hernández, 2022). In contrast, consumption below 10 L kg^{-1} of DPC is considered indicative of efficient water management within the processing system.

Accordingly, the WMIWCP values for the systems were determined to be 0.90 for PS1 and 0.97 for PS2, indicating that the practices employed are sustainable, as they exceed the 0.75 threshold. Likewise, the specific water consumption (SWC) values were 3.79 L kg^{-1} of DPC for PS1 and 1.27 L kg^{-1} of DPC for PS2, respectively, both below the reference threshold of 10 L kg^{-1} of DPC. The higher WMIWCP achieved by PS2 is consistent with its lower specific water consumption. Since this indicator integrates water use efficiency during processing, reductions in water demand directly improve the index, reflecting a more efficient use of the resource rather than simply a reduction in absolute water consumption. Consequently, improvements in WMIWCP should be interpreted as evidence of more efficient water management under the evaluated operating conditions, which is consistent with the objectives of sustainable wet coffee processing promoted in Colombia (Leal-Echeverri and Tobón, 2021; FNC, 2026).

These results are consistent with previous reports indicating that ecological wet-processing technologies

can substantially reduce water consumption compared with conventional systems. According to Melo (2023), high water consumption in coffee production can have significant environmental consequences, especially in regions facing water scarcity.

Table 4 presents the results for the percentage of damaged coffee beans according to the technology used. PS2 recorded an average damage of 0.6%, with a standard error of 0.05 and a variability of 28.33%. The values ranged from a minimum of 0.4% to a maximum of 0.8%. On the other hand, PS1 showed a higher

average damage of 0.83%, with a standard error of 0.04 and a lower relative variability of 16.11%, with values ranging between 0.7% and 1.1%. Under the evaluated conditions, a higher percentage of damaged beans was observed in PS1 than in PS2. This difference may reflect the combined influence of the processing configuration and the specific operating conditions under which each system was evaluated.

Figure 4 summarizes the percentage of damaged beans observed for both processing systems under the evaluated conditions.

Table 4. Percentage of damaged beans for PS1 (ECL) and PS2 (ECW).

Sampling	PS1 (%)	PS2 (%)
1	0.8	0.8
2	0.9	0.4
3	1.1	0.8
4	1.0	0.5
5	0.7	0.6
6	0.8	0.4
7	0.7	0.8
8	0.7	0.7
9	0.8	0.4
10	0.8	0.6
Average	0.83	0.60

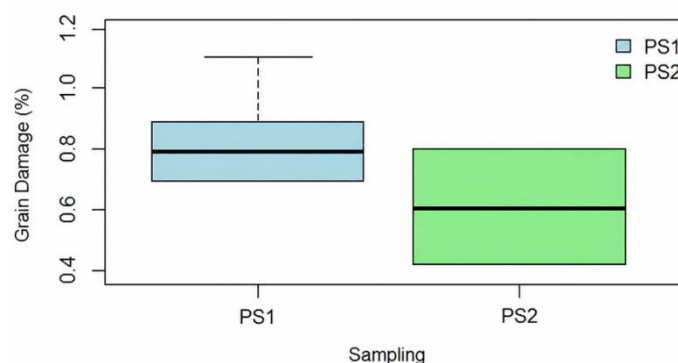


Figure 4. Damaged-bean percentage in 1.0 kg washed coffee samples for PS1 (ECL) and PS2 (ECW).

According to Puerta-Quintero (2013), during the coffee processing stage, beans may exhibit various types of defects. For example, the presence of unpulped beans indicates deficiencies in the mechanical pulping system; crushed beans result from excessive pressure in the machines; and split beans can be attributed to improper handling or malfunctions in the processing equipment. To mitigate these defects and improve the quality of the final product, the implementation of Good Agricultural Practices (GAP) is recommended.

In this context, both the average damage value and its variability should be considered when selecting a coffee processing technology. If the goal is to minimize average bean damage, the ECW technology may represent a more suitable alternative. However, it is important to note that the results obtained are influenced by the specific characteristics of the coffee batch evaluated and the processing conditions. Therefore, a detailed analysis is recommended in each case,

considering other technical and operational factors before making a final decision. The lower percentage of damaged beans observed in PS2 may also be related to differences in the operational sequence of the evaluated systems. Because fermentation precedes the washing stage in PS2, part of the mucilage is naturally degraded before mechanical removal, potentially reducing the mechanical forces required during washing. Consequently, the beans may be subjected to less abrasion and impact during post-harvest operations. Similar observations have been reported for ecological coffee processing systems in which adequate process adjustment and good operational practices contribute to preserving bean physical integrity and reducing mechanical defects (Fajardo-Peña and Sanz-Urbe, 2003; Puerta-Quintero, 2013). Nevertheless, additional experiments under controlled conditions would be necessary to isolate the specific contribution of processing technology from other farm-related factors.

Table 5 presents the results related to the generation of wastewater during the processing of 20 kg of CC using two different technologies. On average, PS2 generated 0.278 L kg⁻¹ of CC in wastewater, with a standard error of approximately 0.0025 L kg⁻¹ and a coefficient of variation of 2.05%. In contrast, PS1 generated 0.625 L kg⁻¹ of CC, with a standard error of approximately 0.017 L kg⁻¹ and a coefficient of variation of 6.17%, indicating greater variability in wastewater generation.

Table 5. Wastewater generation (total volume and L kg⁻¹ of CC) for PS1 (ECL) and PS2 (ECW).

Sampling	PS1 (L)	PS2 (L)
1	12.5	5.7
2	11.8	5.6
3	13.0	5.6
4	11.7	5.5
5	13.5	5.4
Average	12.50	5.56
L.kg ⁻¹ de CC	0.625	0.278

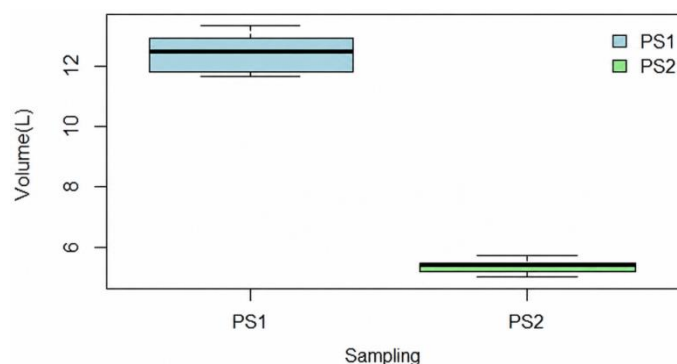


Figure 5. Wastewater volume (L) generated during the processing of 20 kg CC batches using PS1 (ECL) and PS2 (ECW).

The wastewater generated during the post-harvest processing of coffee represents a significant environmental concern due to its complex composition and high pollutant load. This wastewater contains various organic compounds and complex organic constituents, such as caffeine, melanoidins, lignins, tannins, humic acids, and polysaccharides. The impact extends beyond the natural environment, also affecting public health, soil quality, and ecosystem balance, with direct implications for social well-being and sustainable development. In this context, it is essential to implement strategies that reduce the pollutant load of the water used, particularly during critical stages such as pulping, and to promote the sustainable utilization of waste generated during coffee processing (Fernández-Cortés et al., 2020; González-Freire and Martínez-Hernández, 2022).

Table 6 presents the physicochemical characteristics of the wastewater generated by the two processing systems and indicates the degree of contamination and potential need for treatment.

Figure 5 shows that PS2 generated a lower wastewater volume per kilogram of processed cherry coffee than PS1 under the evaluated conditions. Coffee mucilage wastewater in Colombia has been reported to reach COD concentrations exceeding 25,000 mg L⁻¹ and high levels of total solids, confirming the severity of the pollutant load typically associated with wet processing (Montes et al., 2023).

In Colombia, Resolution 631 of 2015 from the Ministry of Environment and Sustainable Development establishes the maximum permissible limits for the discharge of wastewater from the coffee industry (Resolución 631, 2015). When comparing these values with the results obtained, it can be observed that coffee wastewater shows a high level of contamination, as it significantly exceeds the permissible limits in all parameters except for fats and oils. This agrees with broader assessments of coffee wastewater, which describe it as a highly contaminated effluent rich in organic matter, phenolics, tannins, and suspended solids, presenting significant challenges for effective treatment (Ijanu et al., 2020).

In this study, the technologies aim to minimize water use during coffee processing; therefore, when a given pollutant mass is contained in a smaller volume of wastewater, pollutant concentrations may increase because of reduced dilution. Although reducing water consumption is one of the principal objectives of eco-friendly coffee processing, lower water use does not necessarily eliminate the environmental challenges associated with wastewater management. On the

contrary, the reduction in dilution water tends to increase the concentration of organic matter and suspended solids in the generated effluent, making appropriate treatment before discharge even more important. Consequently, improvements in water-use efficiency should be accompanied by adequate wastewater management strategies that consider both pollutant concentration and overall environmental impact (Ijanu et al., 2020; Mohd Said et al., 2023).

The results indicate that PS1 and PS2 exhibit BOD₅ and COD concentrations above the permitted limit ($>0.4 \text{ g L}^{-1} \text{ O}_2$). According to Dobrosz-Gómez et al. (2020), a

BOD₅/COD ratio below 0.35 suggests low biodegradability of the effluent, which increases its potential to cause negative environmental impacts if discharged without prior treatment, especially into water bodies. In this study, PS1 showed a BOD₅/COD ratio of 0.51 and PS2 a ratio of 0.37. Both values were above the 0.35 threshold associated with low biodegradability, suggesting that at least part of the organic matter may be amenable to biological treatment. Nevertheless, the high BOD₅ and COD concentrations and their non-compliance with discharge limits demonstrate the need for treatment before final disposal.

Table 6. Physicochemical characteristics of wastewater from PS1 (ECL) and PS2 (ECW) compared with regulatory limits (Resolution 631/2015).

Parameters	Unit	PS1	PS2	Resolution 631 of 2015
Biochemical Oxygen Demand (BOD ₅)	g O ₂ L ⁻¹	22.2	18.4	0.4
Chemical Oxygen Demand (COD)	g O ₂ L ⁻¹	43.7	49.6	3
Fats and Oils	mg L ⁻¹	< 10.0	< 10.0	30
pH	pH	3.80	3.8	5-9
Settleable Solids (SS)	mL L ⁻¹	270.0	950.0	10
Total Suspended Solids (TSS)	g L ⁻¹	27.4	20.6	0.8

Regarding fat and oil content, both processing systems recorded values below the established limit ($<30 \text{ mg L}^{-1}$), which is a favorable aspect. However, the pH values for PS1 and PS2 were 3.8, falling below the range allowed by Resolution 631 of 2015, indicating high acidity that could negatively affect receiving ecosystems.

On the other hand, the settleable solids and total suspended solids exceeded the maximum permissible limits of 10 mL L^{-1} and 0.8 g L^{-1} , respectively. In the case of PS1, 270 mL L^{-1} of settleable solids and 27.4 g L^{-1} of total suspended solids were recorded, while PS2 showed values of 950 mL L^{-1} and 20.6 g L^{-1} , respectively.

The physicochemical characteristics observed in the evaluated effluents are environmentally relevant because acidic pH, together with elevated concentrations of organic matter and suspended solids, can substantially deteriorate receiving water bodies if discharged without adequate treatment. Low pH promotes acidification of aquatic ecosystems, whereas high concentrations of biodegradable and oxidizable organic matter, reflected in elevated BOD₅ and COD values, can promote oxygen depletion during degradation processes of organic matter, creating hypoxic conditions that threaten aquatic organisms. In addition, the high suspended solids content reduces light penetration, limiting photosynthetic activity and contributing to further ecological deterioration (Rattan et al., 2015; Mohd Said et al., 2023; Mohan et al., 2025).

These results show that the wastewater generated during the coffee processing stage requires prior

treatment before being discharged into receiving water bodies to avoid negative impacts on water quality. In this context, the evaluated farms implement management strategies that are low-cost and easy to apply, adapted to their specific conditions.

At La Esperanza farm, the wastewater is mixed with coffee pulp, which is deposited in a pit where it is left to dry and later used as fertilizer on the same crop. The construction of a covered pit for pulp decomposition, without the use of water and using gravity or simple transport mechanisms, can reduce the pollutant load discharged into the environment by up to 74% (González-Freire and Martínez-Hernández, 2022). This method shares similarities with Becolsub[®] technology, which involves mixing pulp and mucilage. The high viscosity of this combination allows for effective retention of over 50% during transport through screw conveyors, enabling better control of the contaminants generated. Furthermore, by eliminating water use in the depulping process, pollutant load can be reduced by up to 72%, achieving an overall mitigation of over 90% during processing (Salazar-Salas et al., 2013).

On the other hand, at El Mirador farm, part of the wastewater is reused as pig feed, while the remainder is discharged into a filtration tank before release. However, further studies are needed to accurately quantify the efficiency of these methods in reducing pollutants. From an environmental perspective, the sustainability of coffee processing should therefore be evaluated considering the entire wastewater management chain rather than only the volume of water consumed. Recent reviews have emphasized that integrating water-saving technologies with resource

recovery and appropriate treatment systems offers greater environmental benefits than reducing water consumption alone, particularly for small-scale coffee producers where centralized treatment infrastructure is often unavailable (Mohd Said et al., 2023; Ijanu et al., 2020).

Beyond differences between processing systems, the environmental concern is associated with the combined occurrence of acidity, biodegradable organic matter, and suspended solids. Previous studies indicate that untreated coffee processing wastewater may also contain phenolic compounds, tannins, caffeine, and other recalcitrant organic constituents that contribute to toxicity and increase the persistence of pollution in aquatic environments. Consequently, direct discharge may promote eutrophication, oxygen depletion, and deterioration of water quality, with potential impacts on aquatic biodiversity and downstream water uses (Mohd Said et al., 2023; Asefaw et al., 2024; Mohan et al., 2025).

The use of coffee husk as a dietary supplement in pig farming may represent an alternative for valorizing this coffee by-product (Santos-Cruz et al., 2025).

In general terms, the observations obtained in the two evaluated processing systems are consistent with previous studies indicating that eco-friendly technologies can reduce water consumption compared with conventional wet processing while improving resource-use efficiency. According to Rodríguez-Valencia (2022), in 2020, coffee production on farms that adopted processing systems based on clean technologies achieved estimated water savings of approximately 10 million cubic meters, along with a significant reduction in pollution levels, measured in terms of COD.

However, it is essential to consider the specific conditions of each farm, as well as variations in the processing methods implemented, when interpreting these results and assessing their applicability to other regions or production contexts.

At the national scale, ecological wet-processing technologies developed by Cenicafe have enabled the Colombian coffee sector to achieve significant environmental improvements, including the reduction of millions of liters of water use per year and the transition toward cleaner production systems (FNC, 2026).

Considering the elevated COD, BOD₅, suspended solids, and acidic pH observed in both processing systems, treatment strategies should primarily target the removal of biodegradable organic matter, suspended solids, and acidity before final discharge. Conventional biological treatments remain suitable for reducing the organic load when wastewater exhibits sufficient biodegradability, whereas integrated treatment trains combining physicochemical and biological processes

generally achieve better overall performance. For effluents containing high concentrations of recalcitrant compounds, recent studies recommend incorporating advanced oxidation processes as polishing treatments because they effectively degrade phenolic compounds, caffeine, and other persistent organics that are not completely removed by conventional biological systems (Mohd Said et al., 2023; Mohan et al., 2025).

From an environmental management perspective, COD, BOD, pH, and total suspended solids should be considered the critical parameters for evaluating coffee processing wastewater because they largely determine oxygen demand, acidification potential, and the physical alteration of receiving water bodies. These parameters are also those most directly associated with compliance with the discharge limits established by Resolution 631 of 2015. Although nutrients such as nitrogen and phosphorus also contribute to eutrophication, the literature consistently identifies organic loading and acidity as the principal factors governing the environmental impact of coffee processing effluents and, therefore, the primary targets for treatment prior to discharge (Rattan et al., 2015; Mohd Said et al., 2023; Asefaw et al., 2024; Mohan et al., 2025).

Taken together, the observed differences among the evaluated variables suggest that the operational sequence of the processing systems may play an important role in their overall performance. In the evaluated configuration, the incorporation of a fermentation stage before washing in PS2 appears compatible with lower water consumption, a higher water management index, and a lower percentage of mechanically damaged beans, whereas PS1 achieved a higher processing throughput. These observations illustrate the operational trade-offs that frequently arise during wet coffee processing, where maximizing productivity does not necessarily coincide with maximizing water-use efficiency or minimizing bean damage. Therefore, technology selection should consider the specific production objectives of each coffee farm, balancing processing capacity, product quality, and environmental performance.

Despite the practical relevance of the findings, some limitations of the experimental design should be acknowledged. The comparison involved two processing systems implemented on two different coffee farms, each with its own environmental conditions, coffee varieties, management practices, and operational characteristics. Consequently, the effects associated with the processing systems cannot be fully separated from farm-specific factors. In addition, the repeated measurements collected within each processing system were intended to characterize operational variability under the evaluated conditions rather than to provide independent experimental replication. Therefore, the

results should be interpreted as evidence obtained under the specific conditions evaluated in this study, and further investigations involving multiple independent farms and replicated experimental units are recommended to strengthen the generalization of these findings.

4. Conclusions

Under the operating conditions evaluated in this study, PS1 (Ecoline®) exhibited a higher processing throughput than PS2 (Ecowasher®). Conversely, PS2 showed lower water consumption and a higher Water Management Index (WMIWCP). These observations describe the performance of the two processing systems evaluated and should be interpreted within the conditions under which the study was conducted.

Under the evaluated conditions, PS2 presented a lower percentage of damaged beans than PS1. This observation may be associated with differences in the configuration and operation of the two processing systems; however, additional studies would be required to isolate the effect of the processing technology from other factors associated with the evaluated farms.

Regarding wastewater generation, PS2 produced a lower wastewater volume per unit of processed coffee than PS1 under the evaluated conditions. However, despite differences in volume, the physicochemical characterization revealed that both technologies generated effluents with BOD₅, COD, and suspended solids above the maximum permissible limits and pH values below the permitted range, underscoring the need for adequate treatment prior to discharge. These findings also highlight that controlling organic load (COD and BOD), suspended solids, and acidity should be considered the primary environmental objectives for coffee wastewater management, while the selection of treatment technologies should be adapted to the pollutant profile of each processing system. Therefore, improvements in water-use efficiency should always be accompanied by appropriate wastewater treatment and management strategies to ensure that reductions in water consumption are accompanied by effective control of the concentrated pollutants remaining in the generated wastewater.

The observations obtained in this study are consistent with previous reports describing the potential of eco-efficient wet-processing systems to reduce water consumption compared with conventional methods. Nevertheless, because the comparison involved two processing systems implemented on different coffee farms, the present results should be interpreted as evidence obtained under the evaluated conditions and should not be generalized without further studies including independent experimental units.

At a broader scale, the adoption of cleaner post-harvest technologies, supported by Cenicafe and the National Federation of Coffee Growers, continues to drive national advances in reducing water use, minimizing contamination, and promoting sustainable coffee production systems across Colombia.

Authors' Contribution

C.F.O.G.: Investigation, Methodology, Data curation, and Writing – original draft. J.G.A.M.: Conceptualization, Methodology, Supervision, and Writing – review and editing. J.A.C.C.: Formal analysis, Data curation, Visualization, and Writing – review and editing. All authors have read and approved the final version of the manuscript.

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Bibliographic References

- APHA, AWWA, WEF., 2017. Standard Methods for the Examination of Water and Wastewater, 23rd Edition. American Public Health Association. <https://www.standardmethods.org>
- Aristizábal, C., Duque, H., 2005. Caracterización del proceso de beneficio de café en cinco departamentos cafeteros de Colombia. Cenicafe, 56(4), 299–318. <https://www.cenicafe.org/es/publications/arc056%2804%29299-318.pdf>
- Asefaw, K.T., Asaithambi, P., Tegegn, M., 2024. Treatment of wet coffee processing wastewater using a pulsed-electrocoagulation process: Optimization using response surface technique. Applied Water Science, 14, 54. <https://doi.org/10.1007/s13201-024-02118-1>
- Campuzano-Duque, L.F., Wohlgemuth-Blair, M., 2022. Estrategias para el mejoramiento del café robusta (*Coffea canephora*) como nuevo cultivo en Colombia. Agricultura, 12(10), 1576. <https://doi.org/10.3390/agriculture12101576>
- Dobrosz-Gómez, I., Gómez-García, M.Á., Ibarra-Taquez, H.N., 2020. Tratamiento de aguas residuales de la industria del café soluble vía Electrocoagulación - Oxidación Anódica. Selección de los electrodos. Revista EIA, 17(34), 1-17. <https://doi.org/10.24050/reia.v17i34.1328>

- ECOM Agroindustrial Corp., 2023. Reducing water consumption for coffee harvests. <https://www.ecomtrading.com/sustainability-programmes/protect-nature/reducing-water-consumption-for-coffee-harvests/>
- Fajardo-Peña, I.F., Sanz-Urbe, J.R., 2003. Evaluación de la calidad física del café en los procesos de beneficio húmedo tradicional y ecológico (Ecolsub). *Cenicafé*, 54(4), 286-296. <https://biblioteca.cenicafe.org/handle/10778/253>
- Federación Nacional de Cafeteros (FNC), 2026. Environmental dimension: Sustainability in the Colombian coffee sector. <https://federaciondefcafeteros.org/wp/sustainability/environmental-dimension/>
- Fernández-Cortés, Y., Sotto-Rodríguez, K.D., Vargas-Marín, L.A., 2020. Impactos ambientales de la producción del café, y el aprovechamiento sustentable de los residuos generados. *Producción + Limpia*, 15(1), 93-110. <https://doi.org/10.22507/pml.v15n1a7>
- FNC & Minagricultura., 2024. Overview of the Colombian coffee sector: Production, value chain, and socioeconomic characteristics. Resilience BV / Ministry of Agriculture, Nature and Food Quality. https://resiliencebv.com/wp-content/uploads/2024/08/20240925_Coffee-value-chain-Colombia.pdf
- Giraldo-Quintero, J.J., Niño-Méndez, C.D., Vianchá Sánchez, Z., 2017. Análisis de buenas prácticas en el proceso de beneficio del café: experiencia de estudio en el municipio de Viotá. *Ingeniería Solidaria*, 13(22), 121-136. <https://doi.org/10.16925/in.v13i22.1839>
- González-Freire, A., Martínez-Hernández, C., 2022. Mejoramiento y uso de los efluentes para el beneficio del café. *Revista Ciencias Técnicas Agropecuarias*, 31(2), 1-7. <http://scielo.sld.cu/pdf/rcta/v31n2/2071-0054-rcta-31-02-e08.pdf>
- Hernández-García, F.J., 2024. Eficiencia en el consumo de agua en el beneficio húmedo cafetero la HAMMONIA & CIA. LTDA, localizada en el departamento de Jinotega, en el año 2023. *Revista Torreo Universitario*, 1(1), 100-106. <https://doi.org/10.5377/rtu.v1i1.19046>
- Ijanu, E.M., Kamaruddin, M.A., Norashiddin, F.A., 2020. Coffee processing wastewater treatment: A critical review on current treatment technologies with a proposed alternative. *Applied Water Science*, 10(11). <https://doi.org/10.1007/s13201-019-1091-9>
- Leal-Echeverri, J.C., Tobón, C., 2021. The water footprint of coffee production in Colombia. *Revista Facultad Nacional de Agronomía Medellín*, 74(3). http://scielo.org.co/scielo.php?script=sci_arttext&pid=S0304-28472021000309685
- Marín-López, S.M., Arcila-Pulgarín, J., Montoya-Restrepo, E.C., Oliveros-Tascón, C.E., 2003. Relación entre el estado de madurez del fruto del café y las características de beneficio, rendimiento y calidad de la bebida. *Cenicafé* 54(4), 297-315. <https://www.cenicafe.org/es/publications/arc054%2804%29297-315.pdf>
- Melo, C. La importancia del agua en la producción de café. Era of We. <https://www.eraofwe.com/coffee-lab/es/articles/la-importancia-del-agua-en-la-producción-de-cafe> . 4 May. 2023
- MINCIT. Ministerio de Comercio Industria y Turismo. Perfil económico y comercial de Colombia. <https://www.mincit.gov.co/getattachment/estudios-economicos/perfiles-economicos-y-comerciales/en-este-espacio-encontrara-los-perfiles-economicos/america/america-del-sur/colombia/febrero-2024/oe-np-perfil-colombia-28feb24.pdf.aspx> . 28 Feb. 2024.
- Mohan, G., Behera, S.K., Shanthakumar, S., 2025. Advanced oxidation processes for coffee processing wastewater treatment: A comprehensive review. *Journal of Water Process Engineering*, 69, 106737. <https://doi.org/10.1016/j.jwpe.2025.106737>
- Mohd Said, N.S., Abdullah, S.R.S, Ismail, N.I., Hasan, H.A., Othman, A.R., 2023. Towards zero-waste discharge in coffee processing: A review of coffee processing, wastewater treatment and resource valorization. *Journal of Cleaner Production*, 386, 135837. <https://doi.org/10.1016/j.jclepro.2022.135837>
- Montes, C.A., Ortiz, N.V., Arias, C.A., Rodríguez-Chaparro, T., 2023. Vertical flow wetlands as the core for the sustainable treatment of coffee wastewater in small communities in Colombia: Preliminary results. *Water Science and Technology*, 88(8), 1974-1981. <https://doi.org/10.2166/wst.2023.328>
- Montilla-Pérez, J., Arcila-Pulgarín, J., Aristizábal-Loaiza, M., Montoya-Restrepo, E.C., Puerta-Quintero, G.I., Oliveros-Tascón, C.E., Cadena-Gómez, G., 2008. Propiedades físicas y factores de conversión del café en el proceso de beneficio. *Cenicafé* 370, 1-8. <https://biblioteca.cenicafe.org/bitstream/10778/358/1/avt0370.pdf>
- Ochoa-Henriquez, V.H., Faggioli, V., Gómez-Godínez, L.J., Rivarola, M., Cristancho, M., 2024. Colombian coffee (*Coffea arabica* L.) plantations: A taxonomic and functional survey of soil fungi. *Frontiers in Sustainable Food Systems*, 8. <https://doi.org/10.3389/fsufs.2024.1345383>
- Oliveros, C.E., Sanz, J.R., 2011. Ingeniería y café en Colombia. *Revista de Ingeniería*, 33, 99-114. http://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S0121-49932011000100011
- Oliveros-Tascón, C.E., Ramírez, C.A., Rodríguez-Valencia, N., Sanz-Urbe, J.R., Tibaduiza-Vianchá, C.A., 2022. Manejo y aprovechamiento de las aguas residuales del lavado del café con la tecnología ECOMILL®. *Avances Técnicos Cenicafé*, 538, 1-8. <https://doi.org/10.38141/10779/0538>
- Ovalle-Castiblanco, A.M., Cárdenas-Aguirre, D.M., Jiménez-Varón, C.F., Abendaño-Beltrán, C.A., 2022. Influence of field slope on manual harvesting indicators on citrus in the agricultural sector in Caldas-Colombia. *Ingeniería y Competitividad*, 24, (1). <https://doi.org/10.25100/iy.24i1.10996>
- Penagos. 2019a. Unidad de beneficio ecológico para café ECOLINE-400, ficha técnica. <https://penagos.com/productos/unidad-de-beneficio-ecologico-para-cafe-ecoline-400/>

Penagos. 2019b. Ecowasher-300, Ficha técnica. <https://penagos.com/productos/ecowasher-300/>

Puerta-Quintero, G.I., 2013. Calidad del café. En Federación Nacional de Cafeteros de Colombia, Manual del cafetero colombiano: Investigación y tecnología para la sostenibilidad de la caficultura. Cenicafe, 3, 81-110. https://biblioteca.cenicafe.org/bitstream/10778/4346/1/cenbook-0026_30.pdf

Rattan, S., Parande, A.K., Nagaraju, V.D., Ghiwari, G.K., 2015. A comprehensive review on utilization of wastewater from coffee processing. *Environmental Science and Pollution Research*, 22, 6461–6472. <https://doi.org/10.1007/s11356-015-4079-5>

Resolución 631 de 2015, 1, Ministerio de Ambiente y Desarrollo. <https://www.minambiente.gov.co/wp-content/uploads/2021/11/resolucion-631-de-2015.pdf> 17 Mar. 2015.

Rivillas, A.M., 2022. Paisaje cafetero de la montaña de Ibagué, Colombia: un estudio ecológico a escala de geofacies y geotopos. *Cuadernos de Geografía: Revista Colombiana de Geografía* 31(1). <https://doi.org/10.15446/rcdg.v31n1.80997>

Rodríguez-Valencia, N., Duque-Orrego, H., Jaramillo-Cardona, C.M., Quintero-Tepes, L.V., 2022. Adopción del beneficio ecológico del café en Colombia. *Avance Técnico Cenicafe*, 543,1-12. <https://doi.org/10.38141/10779/0543>

Rodríguez-Valencia, N., Sanz-Urbe, J., Oliveros-Tascón, C., Ramírez-Gómez, C., 2015. Beneficio de Café en Colombia. *Avances Técnicos Cenicafe*, p.35.

Salazar-Salas, L.A., Quiroga-Mateus, R.Y., Castillo-Rojas, L.F., Vega-Serrano, H.A., 2013. Diagnóstico del tratamiento de aguas residuales mediante los sistemas Cenicafe y Majavita del beneficio ecológico del café con módulo becolsub en la hacienda Majavita. *Innovando En La U*, 5, 33-48. <https://revistas.unilibre.edu.co/index.php/innovando/article/view/3846>

Santos-Cruz, R., Castro-Díaz, E.I., Rodríguez-Lozano, A., Domínguez, Z., Yáñez-Pizaña, A., Sánchez-Salcedo, J.A., 2025. Supplementation with coffee husk enhances lactational performance of piglets and IgG concentration in sow colostrum: A prepartum intervention. *Agro Productividad*, 18(4), 123-131. <https://revista-agroproductividad.org/index.php/agroproductividad/article/view/3077/2627>

World Economic Forum., 2025. Lessons from Colombia's sustainable coffee sector and its insights for climate solutions. <https://www.weforum.org/stories/2025/06/columbias-sustainable-coffee-sector-and-its-lesson-for-climate-solutions/>