ENVIRONMENTAL ASSESSMENT OF AIR EMISSIONS FROM HYDRO-ROASTING COMPARED TO CONVENTIONAL DRY ROASTING

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ABSTRACT

Coffee roasting is an energy-intensive thermal process that generates gaseous and particulate emissions with potential environmental impacts [1], [2]. In response to the increasing demand for sustainable food processing technologies, Hydro-Roast has been proposed as a moisture-assisted roasting approach to modify heat transfer behavior and potentially reduce pollutant generation. This study presents a preliminary environmental assessment of Hydro-Roast through comparison with conventional dry roasting under laboratory-scale conditions.

Experiments were conducted using Robusta coffee beans under light, medium, and dark roasting conditions. Carbon dioxide emissions were continuously monitored using a Testo 350 XL flue gas analyzer, while particulate matter emissions were determined using a gravimetric sampling method.

The results indicated that Hydro-Roast consistently exhibited lower CO_2 emissions than conventional roasting, with average reductions of 13.07%, 15.28%, and 14.66% for light, medium, and dark roasts, respectively. Particulate matter emissions also showed lower generation tendencies, with estimated reductions ranging from 7.7% to 13.6% depending on roasting intensity. Hydro-Roasting consistently reduced both carbon dioxide and particulate matter emissions.

The findings provide preliminary scientific evidence supporting the environmental potential of Hydro-Roast and suggest that moisture-assisted roasting may represent a promising strategy for the development of more sustainable coffee roasting technologies.

Keywords: *Carbon dioxide emissions, Coffee roasting, Environmental assessment, Hydro-Roasting, Particulate matter.*

1. INTRODUCTION

Coffee is one of the most important agricultural commodities worldwide and represents a major component of the global food and beverage industry. According to recent international market reports, global coffee production and consumption have continuously increased due to growing consumer demand and the expansion of specialty coffee markets. Vietnam is recognized as one of the world's leading coffee-producing countries, particularly for Robusta coffee, contributing significantly to the international coffee supply chain. Consequently, improving the sustainability of coffee production and processing has become an increasingly important objective for both industrial development and environmental protection [5], [6].

Among the various post-harvest processing stages, coffee roasting is one of the most energy-intensive operations. Roasting transforms green coffee beans into commercially valuable products through a series of complex physical and chemical reactions, including moisture evaporation, Maillard reactions, caramelization, and thermal degradation. These reactions are responsible for the development of desirable coffee aroma, flavor, and color characteristics while simultaneously generating gaseous and particulate emissions [1], [2], [3], [10].

Previous studies have demonstrated that coffee roasting can release various atmospheric pollutants associated with thermal decomposition of organic compounds within the coffee bean matrix. Carbon dioxide is generated through oxidation and thermal degradation reactions, while particulate matter may originate from carbonization, fragmentation of bean structures, and the release of fine solid particles during roasting operations. The environmental impact of these emissions has attracted increasing attention as coffee processing industries seek cleaner production technologies capable of reducing pollutant generation and greenhouse gas emissions [3], [4].

Conventional coffee roasting primarily relies on dry heat transfer mechanisms, where thermal energy is transferred from hot air to the coffee bean surface and subsequently conducted toward the bean interior. Under intensive roasting conditions, significant temperature gradients may develop within the bean structure, potentially promoting localized overheating and accelerating thermal decomposition reactions. Such conditions may increase the formation of gaseous and particulate emissions associated with roasting processes [9], [19].

Moisture-assisted thermal processing has been widely investigated in thermal engineering and biomass treatment applications because of its influence on heat transfer behavior and reaction kinetics. Water possesses a relatively high specific heat capacity and latent heat of vaporization, enabling it to absorb substantial amounts of thermal energy during heating processes. The presence of moisture may therefore reduce excessive temperature gradients, moderate thermal stress, and delay severe thermal degradation under controlled operating conditions. Similar thermal buffering mechanisms have been reported in various food and biomass processing systems [8], [9], [22], [23].

Inspired by these moisture-assisted thermal principles, Hydro-Roasting was developed as a coffee roasting approach intended to investigate whether controlled moisture conditioning could influence roasting-related environmental emissions. Unlike conventional dry roasting, Hydro-Roasting incorporates moisture treatment before thermal processing, potentially modifying internal heat transfer behavior and roasting kinetics while maintaining roasting performance.

Although considerable research has been conducted on conventional coffee roasting chemistry and roasting emissions, environmental investigations specifically addressing Hydro-Roasting remain limited. In particular, comparative experimental information regarding carbon dioxide emissions, particulate matter generation, and the environmental implications of moisture-assisted coffee roasting is currently unavailable. Establishing a preliminary scientific understanding of these environmental characteristics may contribute to the development of cleaner coffee roasting technologies and more sustainable coffee processing systems.

Inspired by moisture-assisted [9], [22], [23] thermal treatment concepts, Hydro-Roasting was developed as a roasting approach intended to investigate whether controlled moisture conditioning could modify roasting behavior and influence atmospheric emissions. Unlike conventional dry roasting, Hydro-Roasting incorporates moisture treatment before roasting, potentially altering heat transfer characteristics and thermal reaction pathways.

Despite the theoretical potential of moisture-assisted roasting, comparative environmental information regarding carbon dioxide emissions and particulate matter generation under Hydro-Roasting conditions is currently unavailable. Establishing an initial scientific understanding of these environmental characteristics may contribute to the development of cleaner and more sustainable coffee roasting technologies.

Therefore, this study was designed to experimentally compare Hydro-Roasting and conventional dry roasting through evaluation of carbon dioxide emissions, particulate matter generation, and their potential environmental implications under laboratory-scale roasting conditions.

2. RESEARCH METHODS

2.1. Experimental Framework

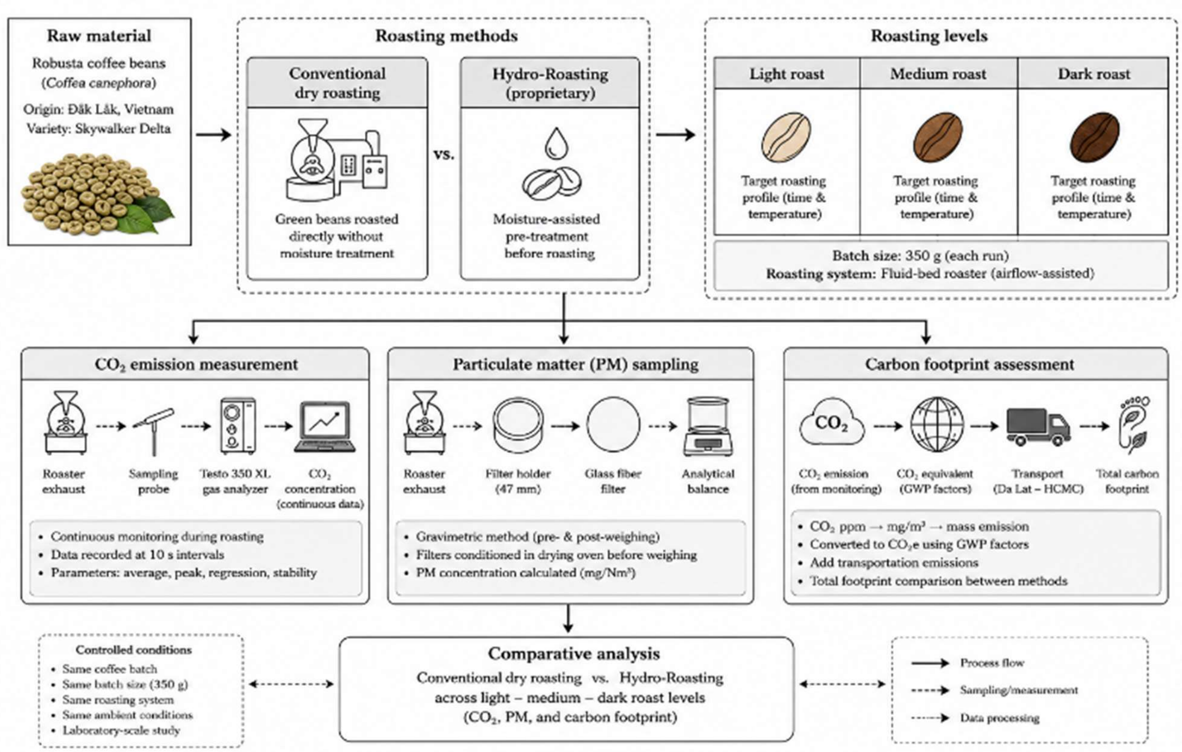
This study was designed to comparatively evaluate the environmental emission characteristics of Hydro-Roasting and conventional dry coffee roasting under controlled laboratory conditions. Commercial Robusta coffee beans [5] obtained from Đắk Lắk Province, Vietnam, were used throughout the investigation to minimize variability associated with bean origin and raw material properties. The experimental methodology focused on evaluating the influence of moisture-assisted roasting on atmospheric emissions and greenhouse gas implications.

Two roasting approaches were investigated:

• Conventional dry roasting;

• Hydro-Roasting with proprietary moisture-assisted pre-treatment.

For each roasting method, experiments were performed under three roasting levels, including light, medium, and dark roasting conditions. Comparative environmental evaluation was conducted through continuous CO_2 monitoring, filter-based particulate matter sampling.



The overall experimental framework was developed to investigate whether moisture-assisted roasting could influence emission generation and environmental performance under comparable roasting conditions.

2.2. Materials and Roasting Conditions

Commercial Robusta coffee beans (*Coffea canephora*) supplied from Đắk Lắk Province, Vietnam, were used for all experiments. To reduce experimental variability, the same coffee batch was maintained throughout the study.

Coffee roasting experiments were conducted using a fluid-bed roasting system [24], [26], [28] operating under airflow-assisted heat transfer. The roasting equipment allowed control of roasting temperature, airflow intensity, roasting duration, and thermal profile. A batch size of 350 g was used for each experimental run to maintain consistency between roasting conditions.

Conventional dry roasting was performed by directly introducing green coffee beans into the roasting chamber. For Hydro-Roasting experiments, coffee beans underwent a proprietary moisture-assisted pre-treatment before roasting. Following the pre-treatment stage, the beans were stabilized under controlled conditions prior to thermal processing to improve process consistency between experimental runs.

Roasting experiments were performed under three roasting levels: (i)Light roast; (ii) Medium roast; (iii) Dark roast.

Representative roasting profiles were established to maintain repeatability and ensure comparable roasting conditions for both roasting methods.

2.3. Carbon Dioxide Measurement

Carbon dioxide emissions generated during roasting were continuously monitored using a Testo 350 XL flue gas analyzer. The analyzer was connected to the roasting exhaust system through a gas sampling probe positioned near the roasting outlet to continuously record emission behavior during roasting development.

The emission monitoring system was designed primarily for comparative laboratory-scale analysis rather than absolute industrial stack emission measurements. Before each experimental run, the analyzer was stabilized according to manufacturer operating procedures to improve measurement consistency.

CO_2 concentrations were continuously recorded throughout the roasting process under light, medium, and dark roasting conditions. The measured data were subsequently processed to determine average concentrations, peak concentrations, regression characteristics, emission stability, and greenhouse gas implications.

2.4. Particulate Matter Measurement

Particulate matter emissions were evaluated using a filter-based gravimetric sampling method [11], [12], [14] connected directly to the roasting exhaust system. The sampling procedure was adapted from standard particulate emission monitoring principles and designed for comparative evaluation between roasting methods.

During sampling, exhaust gases passed through glass microfiber filters where suspended particles were collected. Following each experiment, the filters were conditioned and reweighed using an analytical balance. The difference between pre- and post-sampling filter masses was used to determine particulate matter accumulation according to gravimetric principles.

The comparative PM analysis was performed under identical roasting conditions for both conventional dry roasting and Hydro-Roasting to evaluate differences in particulate generation tendencies.

2.5. Data Processing and Statistical Analysis

Experimental data were processed using comparative statistical analysis to evaluate emission behavior under different roasting conditions. The analysis included calculation of average emission concentrations, peak emission values, standard deviations, emission reduction percentages, and linear regression characteristics [16], [17].

Regression models were applied to investigate emission accumulation behavior during roasting development, while slope coefficients and coefficients of determination were used to evaluate emission stability and temporal trends. Comparative analyses were conducted for light, medium, and dark roasting conditions to determine the environmental performance of Hydro-Roasting relative to conventional dry roasting [17].

3. RESEARCH RESULTS

3.1. Carbon Dioxide Emissions

The average carbon dioxide concentrations obtained from three independent roasting experiments are presented in Figure 2 and Table 2.

Hydro-Roasting consistently generated lower CO_2 concentrations than conventional dry roasting under all roasting conditions investigated. The difference between the two roasting methods became evident across light, medium, and dark roasting levels, indicating that the moisture-assisted roasting approach may influence thermal decomposition behavior throughout the roasting process.

The average CO_2 concentration for conventional roasting increased from 1598.78 ppm during light roasting to 2198.02 ppm during dark roasting. A similar increasing trend was observed for Hydro-Roasting, where average concentrations increased from 1389.80 ppm to 1875.78 ppm as roasting severity increased.

Comparison between roasting methods demonstrated average CO_2 reductions of 13.07%, 15.28%, and 14.66% for light, medium, and dark roasting conditions, respectively. The highest reduction efficiency was observed during medium roasting, while comparable reductions were obtained under light and dark roasting conditions.

The results suggest that moisture-assisted roasting may moderate thermal reactions occurring during coffee roasting and contribute to lower carbon dioxide generation under comparable roasting conditions.

3.2. Carbon Dioxide Emission Assessment

Carbon dioxide emissions generated during coffee roasting were continuously monitored using the Testo 350 XL flue gas analyzer under controlled laboratory conditions. To improve the reliability of the experimental observations, each roasting condition was independently repeated three times under identical operating conditions. The recorded CO_2 concentrations obtained from the repeated experiments were statistically processed to generate representative emission values for comparative analysis between conventional dry roasting and Hydro-Roasting.

The arithmetic mean of the measured CO_2 concentrations was calculated according to:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

Where:

- $\bar{x}$: average CO_2 concentration (ppm);
- x_i: measured CO_2 concentration;
- n: number of experimental repetitions (n = 3).

Experimental variability was evaluated through the standard deviation:

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

Where:

- SD: standard deviation;
- x_i: measured CO_2 concentration;
- $\bar{x}$: average CO_2 concentration;
- n: number of repetitions.

The calculated standard deviation values were used to assess measurement repeatability and reduce the influence of random fluctuations during roasting experiments.

To evaluate the environmental performance of Hydro-Roasting relative to conventional dry roasting, the CO_2 emission reduction efficiency was calculated as:

$$Reduction(\%) = \frac{C_{Dry} - C_{Hydro}}{C_{Dry}} \times 100$$

where C_{Dry} and C_{Hydro} represent the average CO_2 concentrations obtained from conventional dry roasting and Hydro-Roasting, respectively.

The processed average CO_2 concentrations obtained from the three independent experiments are presented in Figure 2, while the corresponding numerical values and calculated reduction efficiencies are summarized in Table 1.

Table 1. *Average CO_2 emission characteristics of conventional dry roasting and Hydro-Roasting obtained from three independent experiments (n = 3).*

Roast level	Dry (ppm)	Hydro (ppm)	ΔCO_2(ppm)	Reduction (%)
Light	1598.78	1389.80	208.98	13.07
Medium	1889.23	1600.61	288.62	15.28
Dark	2198.02	1875.78	322.24	14.66

Hydro-Roasting consistently exhibited lower average carbon dioxide concentrations than conventional dry roasting under all roasting conditions investigated. Conventional roasting produced average CO_2 concentrations ranging from 1598.78 ppm during light roasting to 2198.02 ppm during dark roasting. A similar increasing trend was observed for Hydro-Roasting, where average concentrations increased from 1389.80 ppm to 1875.78 ppm with increasing roasting intensity.

The calculated reduction efficiencies demonstrated that Hydro-Roasting reduced average CO_2 emissions by 13.07%, 15.28%, and 14.66% for light, medium, and dark roasting conditions, respectively. The greatest reduction was observed during medium roasting, while relatively consistent emission reductions were maintained throughout the investigated roasting range.

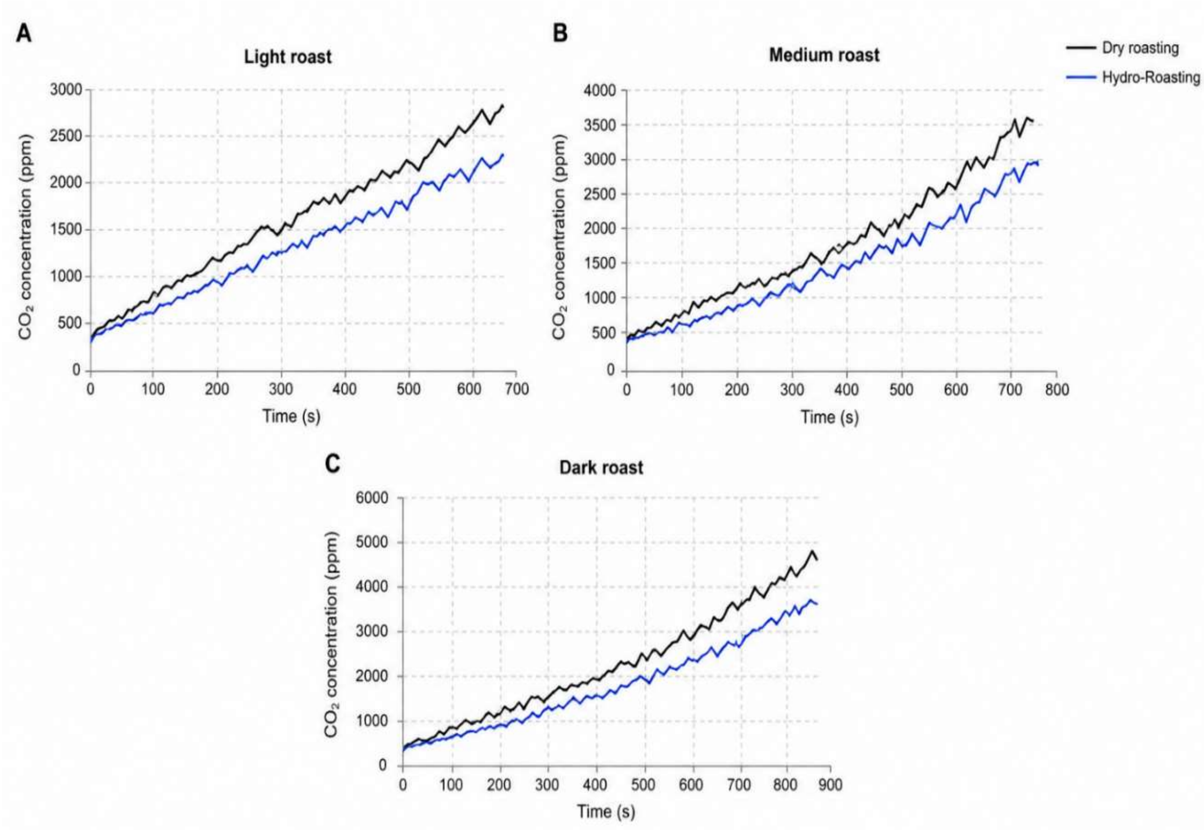


Figure 2. *CO_2 emission profiles during conventional dry roasting and Hydro-Roasting under (A) light, (B) medium, and (C) dark roasting conditions. Each profile represents the average behavior obtained from three independent roasting experiments (n = 3).*

The observed emission behavior indicates that Hydro-Roasting may contribute to lower carbon dioxide generation under comparable roasting conditions. The relatively stable reduction efficiencies across different roasting levels further suggest that the environmental influence of moisture-assisted roasting may be maintained throughout the roasting process rather than being restricted to a particular roasting stage.

3.3. Particulate Matter Emission Assessment

Particulate matter emissions generated during coffee roasting were evaluated using a filter-based gravimetric sampling system connected directly to the roasting exhaust outlet. The overall sampling procedure adopted in this study is illustrated in Figure 3. During roasting, exhaust gases generated from the coffee roaster were transported through the exhaust duct to the isokinetic sampling point, where suspended particulate matter was collected using a PM filter holder connected to a vacuum pump. After completion of each experimental run, the collected filter samples were subjected to gravimetric analysis, and the resulting data were processed for comparative evaluation between conventional dry roasting and Hydro-Roasting.

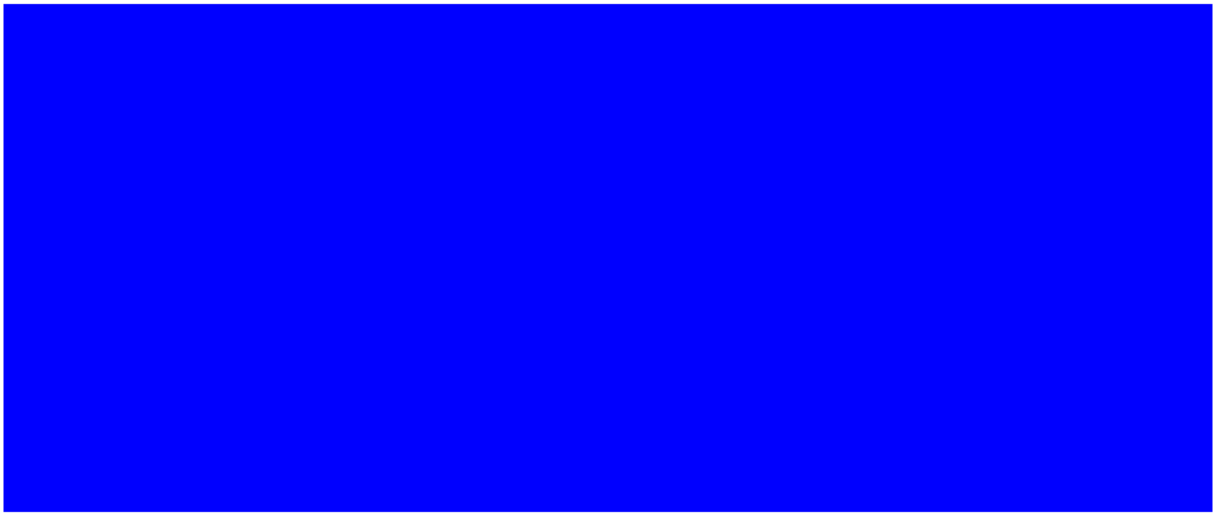


Figure 3. *Schematic representation of the gravimetric particulate matter sampling system used for roasting emission monitoring.*

During roasting, exhaust gases generated from the coffee roaster were transported through the exhaust duct to an isokinetic sampling point, where suspended particulate matter was collected on a filter medium connected to a vacuum-assisted sampling system. The collected samples were subsequently subjected to gravimetric analysis and data processing for comparative evaluation.

The particulate matter collected during each experimental run was determined from the difference between the filter mass before and after sampling according to:

$$PM = m_f - m_i$$

where

- PM : *particulate matter collected,*
- m_f : *filter mass after sampling,*
- m_i : *initial filter mass before sampling.*

To improve experimental reliability, each roasting condition was independently repeated three times, and the average

particulate matter emission was calculated as:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

where: n = 3.

The relative particulate matter reduction efficiency of Hydro-Roasting compared with conventional dry roasting was determined as:

$$PM\ Reduction(\%) = \frac{PM_{Dry} - PM_{Hydro}}{PM_{Dry}} \times 100$$

The processed particulate matter emission behavior for both roasting methods is summarized in Table 2.

The comparative particulate matter emission behavior between the two roasting methods is presented in Figure 4. The results demonstrate that PM emissions increased progressively with roasting severity for both roasting methods. However, Hydro-Roasting consistently maintained lower particulate matter concentrations throughout the investigated roasting conditions, indicating that the presence of moisture may influence particle formation during thermal processing.

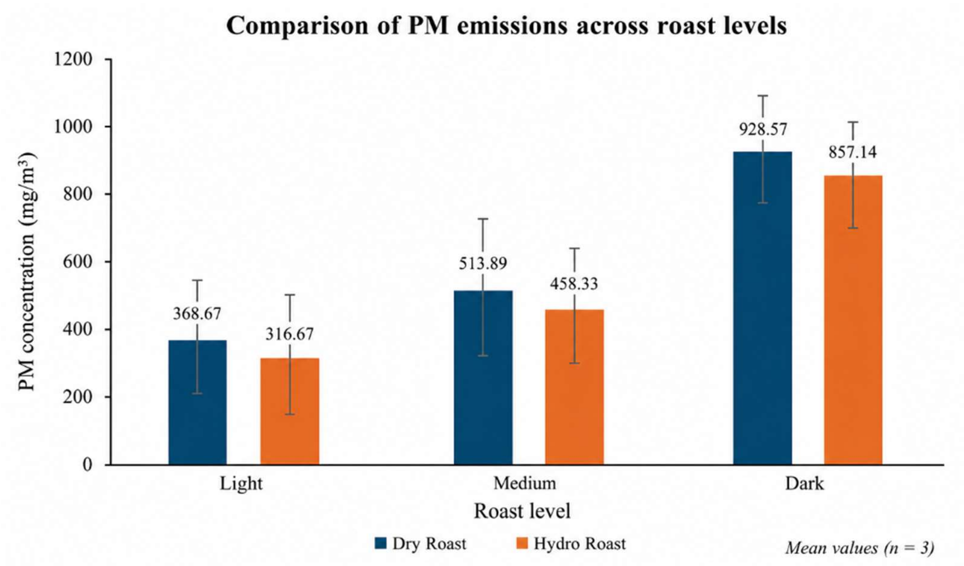


Figure 4. *Comparison of particulate matter emissions between Hydro Roasting and conventional dry roasting under different roast conditions.*

The quantitative particulate matter emission characteristics are summarized in Table 2. Conventional dry roasting generated average PM concentrations of 383.33 mg/m^3, 513.89 mg/m^3, and 904.73 mg/m^3 for light, medium, and dark roasting conditions, respectively. Under identical roasting conditions, Hydro-Roasting produced lower average PM concentrations of 316.67 mg/m^3, 458.33 mg/m^3, and 857.10 mg/m^3.

Table 2. *Average particulate matter emission characteristics of conventional dry roasting and Hydro-Roasting obtained from three independent experiments (n = 3).*

Roast level	Dry (mg/m^3)	Hydro (mg/m^3)	ΔPM (mg/m^3)	Reduction (%)
Light	383.33	316.67	66.66	17.39
Medium	513.89	458.33	55.56	10.81
Dark	904.73	857.10	47.63	5.26

The calculated particulate matter reduction efficiencies were 17.39% for light roasting, 10.81% for medium roasting, and 5.26% for dark roasting. Although particulate matter emissions increased with roasting intensity for both roasting methods, Hydro-Roasting consistently exhibited lower PM generation than conventional roasting. The reduction efficiency gradually decreased as roasting severity increased, suggesting that the moderating influence of moisture on thermal degradation may become less significant under more intensive roasting conditions, where pyrolysis and carbonization reactions increasingly dominate particulate formation.

Overall, the particulate matter assessment indicates that Hydro-Roasting consistently reduced airborne particulate emissions under equivalent roasting conditions. The observed reduction trend supports the hypothesis that moisture-assisted roasting may suppress excessive thermal degradation and particle fragmentation during coffee roasting, thereby contributing to improved environmental performance compared with conventional dry roasting.

4. Discussion

4.1. Mechanisms of CO_2 Reduction

The present study demonstrated that Hydro-Roasting consistently generated lower carbon dioxide emissions than conventional dry roasting under comparable roasting conditions. This behavior can be explained by the combined effects of moisture-assisted heat transfer and modifications in the thermal degradation pathways of coffee bean constituents.

Coffee roasting [1], [3], [10] involves simultaneous moisture evaporation, Maillard reactions, caramelization, and pyrolysis of carbohydrates, proteins, and lipids. As roasting progresses, structural polysaccharides such as cellulose and hemicellulose undergo thermal decomposition, producing gaseous products including CO_2 and CO together with volatile compounds and carbonaceous residues. A simplified representation of biomass pyrolysis [7], [8], [20] may be expressed as:

$$(C_6H_{10}O_5)_n \xrightarrow{\Delta} \text{Solid carbon} + CO_2 + CO + H_2O + \text{Organic volatiles}$$

During Hydro-Roasting, additional moisture is present within the roasting system. Water possesses a relatively high specific heat capacity and latent heat of vaporization. Before extensive thermal decomposition can occur, part of the supplied thermal energy is consumed through water evaporation :

$$H_2O(l) \xrightarrow{\Delta H_{vap}} H_2O(g) \text{ [19]}$$

This process absorbs a considerable amount of thermal energy and may reduce localized overheating around the coffee bean surface. Consequently, excessive thermal gradients and rapid pyrolysis reactions are moderated, delaying intense thermal degradation and reducing gaseous emission formation [9], [19].

The relatively stable CO_2 reduction observed across light, medium, and dark roasting conditions suggests that the thermal buffering effect of moisture may operate throughout the roasting process rather than being limited to a specific roasting stage [9], [22], [23]. Similar heat and mass transfer phenomena have been reported in biomass thermal processing and industrial drying studies.

4.2. Mechanisms of Particulate Matter Reduction

Particulate matter generated during coffee roasting originates from the thermal degradation and fragmentation of coffee bean structures under elevated temperatures. PM formation is associated with carbonization, char production, and the release of fine carbonaceous particles during roasting development. A simplified thermal degradation pathway may be represented as:

$$\text{Organic matter} \xrightarrow{\Delta} \text{Char} + \text{Fine carbonaceous particles} + \text{Gas [7], [8], [20]}$$

The experimental results obtained in this study demonstrated that Hydro-Roasting consistently reduced particulate matter emissions compared with conventional dry roasting. The reduction efficiency was highest under light roasting conditions and gradually decreased as roasting severity increased.

This behavior may be explained by the influence of retained moisture on the physical and thermal properties of coffee beans. Moisture can improve heat distribution within the bean matrix and reduce excessive thermal stress during roasting. More uniform heating may decrease structural cracking and suppress uncontrolled fragmentation [7] of carbonized materials, thereby reducing airborne particulate generation.

As roasting severity increases, pyrolysis and carbonization reactions become progressively more dominant. Under dark roasting conditions, the formation of char and thermally degraded structures intensifies, reducing the relative influence of moisture-assisted thermal buffering. This observation is consistent with the decreasing PM reduction efficiency obtained experimentally [8], [20].

4.3. Environmental Implications of Hydro-Roasting

The combined reduction of carbon dioxide and particulate matter emissions observed in this study suggests that Hydro-Roasting may provide environmental advantages over conventional dry roasting. Lower CO_2 emissions [6] indicate reduced gaseous release during thermal processing, while lower particulate matter generation may contribute to improved workplace air quality and cleaner roasting operations.

Unlike conventional roasting, where rapid heat transfer may promote excessive thermal degradation, Hydro-Roasting introduces a moisture-assisted thermal environment that moderates roasting reactions while maintaining roasting progression. The simultaneous reduction of gaseous and particulate emissions indicates that moisture-assisted roasting may improve the environmental performance of coffee roasting without fundamentally altering the roasting process itself [13].

Although the present study was conducted under laboratory-scale conditions, the experimental findings suggest that Hydro-Roasting has potential for further development as an potentially cleaner roasting approach. Additional investigations under larger-scale operating conditions would provide a more comprehensive understanding of its practical applications in sustainable coffee processing [6].

5. Conclusions

This study comparatively evaluated carbon dioxide and particulate matter emissions generated during conventional dry roasting and Hydro-Roasting of coffee under controlled laboratory conditions. Experimental results demonstrated that Hydro-Roasting consistently produced lower emissions than conventional roasting across the investigated roasting conditions.

Hydro-Roasting reduced average carbon dioxide emissions by approximately ***13–15%,*** while particulate matter emissions were reduced by approximately ***5–17%*** depending on roasting severity. The observed emission behavior is consistent with the proposed mechanisms of moisture-assisted heat transfer, thermal buffering, delayed pyrolysis, and reduced excessive carbonization during roasting.

The combined CO_2 and PM results indicate that Hydro-Roasting may improve the environmental performance of coffee roasting processes while maintaining roasting development. These findings provide preliminary experimental evidence supporting Hydro-Roasting as a potentially cleaner roasting approach compared with conventional dry roasting.

Future perspectives

Future research should focus on larger experimental datasets, pilot-scale roasting systems, and advanced analytical techniques to further investigate the influence of moisture on coffee roasting chemistry and emission mechanisms. Additional studies involving industrial-scale validation and detailed characterization of roasting emissions would contribute to a more comprehensive understanding of Hydro-Roasting and support its potential application in sustainable coffee processing technologies [1], [10].

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