

Effect of Oxidative and Non-Oxidative Media on Coffee Torrefaction and Uncondensed-Gas Properties

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ABSTRACT

This research aims to examine the effect of atmospheric media variations on the uncondensed gas characteristics produced from the torrefaction and cooling processes of coffee beans. The process involved using air, N₂, and Ar at a speed of 1 l/min as atmospheric media. Arabica green beans were torrefied for 60 min at 235±8°C and later cooled at the same rate and medium in a fixed-bed torrefier but stopped after the temperature reached 50°C. The volatile gases from the process flowed to the condenser, followed by the separation of the uncondensed gas from the liquid product, and subsequently flowed through the chimney. Furthermore, thermocouples that are connected to the Artisan visual roaster scope as an interface as well as the Artisan 2.4.2 software on a computer to measure and record changes in drum and bean temperatures (°C) over time (min). The uncondensed-gas yield was calculated according to the mass balance principle, and their characteristics were determined directly in the form of temperature distribution (°C) and CO emission (ppm) by placing the testo 310 gas analyser sensor on the chimney. According to the findings, oxidative atmospheric caused greater temperature fluctuations in the drum and beans during the processes than non-oxidative media. The variations in atmospheric media led to differences in yield, and uncondensed-gas temperature distribution, as well as the CO emission. There was an increase in CO emission as the temperature was increased. The CO produced from torrefaction using non-oxidative is lower than using oxidative media. The cost factor and supporting of absorbent uncondensed-gas recycling technology must be taken into account when using non-oxidative media. This application will not only yield product variants but also reduce CO emissions and the coffee industry's carbon footprint.

Key words: Arabica-green-bean; coffee torrefaction; nitrogen; argon; condenser.

1 INTRODUCTION

Coffee is a very competitive commodity which has evolved from a simple crop to a product with high specifications (Pascucci, 2018). Consumers consider not only price and taste, but also the environmental impact and sustainability of consumed products (Fuller; Grebitus, 2023). Manufacturers continue to innovate, providing items that fit the demands of the latest trends (Krishnan, 2017) (Freitas et al., 2024). These innovations increase product diversity and have a favourable impact on a range of areas (Teixeira et al., 2022). These developments increase product diversity and benefit the economy in a number of ways, including the international trade in coffee. Carbon Neutral (CN) is one of the additional costs usually incurred by coffee connoisseurs due to the carbon footprint (CF) of the industry (Hassard et al., 2014) and this is observed to be currently operational in Germany (Birkenberg et al., 2021). This means efforts are required to reduce CF in order to make coffee more competitive (Zhao et al., 2024) and one of the methods to achieve this is through the application of torrefaction technology and condensation of smoked gas as an alternative to roasting (Faisal et al., 2023).

Coffee in the form of green beans has become a mainstay export product for several producing countries

because the plant cannot grow effectively everywhere in the world. Population growth and coffee drinking habits are driving up global coffee consumption, although coffee farmers are not particularly affected by this trend. (Tamru; Minten, 2023). It is important to note that the added value of this commodity is greatly increased after the roasting process normally conducted in export destination countries to maintain the taste quality of the post-roasted coffee as well as to ensure production continuity and price stability. Advancements in packaging technology, information technology, and the current speed of aircraft transportation have made it easy for these products to be transferred easily from one country to the other (Nab; Maslin, 2020). However, the problem of CF persists due to the transportation of the green bean through ships which requires a long period of up to months to reach the designated destination. Customers prefer low CF coffee due to its sustainability and favourable effects on the environment, just like they do for other products. (Rondoni; Grasso, 2021).

A number of roasting technologies are currently in widespread use, including fluidised beds, rotating drums, and hybrids of the two, as well as infrared roasters that can concurrently heat the beans' exterior and inside and other cutting-edge technologies (Das; Duarah; Purkait, 2023). Numerous pollutants, emissions, waste, energy consumption,

and poisons are produced during the roasting process, all of which have an adverse influence on the environment. Recycling, efficiency, ecologically friendly technologies, and the utilisation of renewable energy all lessen negative effects. (Da Costa et al., 2023), (Barrios-Rodríguez et al., 2022), (Tsai; Lee; Huang, 2025). Through effective technological design (heat and combustion) and control systems, coffee roasting equipment can reduce exhaust emissions. (Kljajic; Andjelkovic; Gvozdenac, 2016). The control system integrates AI, IoT, and heat recovery elements to automatically monitor and regulate emissions digitally (Wibowo et al., 2022). A heat exchanger system, thermal insulation, temperature and time management, and an effective cooling system are used to achieve the heat recovery function. By allowing the roaster to repurpose the heat produced, the heat exchanger system lowers energy usage. (Milani; Montorsi; Terzi, 2017).

Roasting is the process of heating products below their ignition temperature to provide incomplete combustion and this often produces harmful smoke (Sruthi et al., 2021). One of the most dangerous elements of the exhaust gas usually produced is the CO emission (Lebouf; Aldridge, 2019) which is mainly detrimental to the health of workers and other people near the operating location (Newton, 2002), (Hawley; Cox-Ganser; Cummings, 2017). CO is a colorless, odorless, tasteless gas that is difficult to detect. It is a highly toxic gas that, if inhaled in sufficient amounts, can be deadly to humans and animals (Varma; Mulay; Chemtob, 2009). Previous research highlighted the dangers of exhaust gases from the biomass product processing industry, including coffee roasters, on human health (Nishimura; Abe; Fukunaga, 2003). Moreover, exposure to diacetyl compounds has been associated with bronchiolitis obliterans, a rare and severe respiratory disease, and total CO volatiles (Echt et al., 2021). It has also been reported that the accumulation of small exhaust gas produced in each industry has a significant impact on the environment (Lyons; Turchi; Gratson, 1995).

There have been many researches on biomass torrefaction and the effect of varying different atmospheric media on the characteristics of the resulting product. Atmospheric media engineering was applied in the process to have a certain type of content in the main product and to determine its impact on by-products such as condensable smoke gas. Inert gas media are used to prevent oxidative O_2 . According to research, low O_2 concentrations slow down the pace of lipid oxidation, which influences the production of dangerous acrylamide. On the other hand, they raise the amounts of antioxidants in coffee beans, which are good for health (Fadri et al., 2019). Moreover, research also focused on utilizing flue heat of flue gases from roasters (Milani; Montorsi; Terzi, 2017) but none was observed to use torrefaction equipped with a condensing gas condenser as an alternative roasting process for coffee beans to minimize pollution and dangers of smoke. The variation of atmospheric media in the torrefaction process can

lead to certain differences in the torrefied coffee as the main product and the liquid smoke as the by-product (Faisal et al., 2022). Coffee torrefaction aligned with sustainability trends and legal frameworks for industrial applications.

The purpose of this research is to examine the effect of varying atmospheric media such as air, N_2 , and Ar on the temperature characteristics and CO emission of uncondensed-gas with respect to time. This is to ensure that the application of torrefaction to coffee beans in producing countries does not only produce useful by-products and reduce the effects of smoke gas pollution, but most importantly decreases the CF from the industry. Product exports from torrefaction coffee will give producing nations more value that is more efficient and successful in ensuring the welfare of farmers. CF reduction benefits the environment and sustainability, while the range of torrefaction products benefits trade. It is important to restate that coffee bean torrefaction is one of the efforts to produce coffee products with better and more competitive specifications.

2 MATERIAL AND METHODS

The raw material used is coffee beans from the Gayo highland coffee plantation, Central Aceh, Indonesia, located at an altitude of 1200 m above sea level. Gayo coffee has been known since the 17th century and has become an important commodity for the trade union (Verenigde Oost-indische Compagnie) belonging to Dutch colonialism and currently has Organic Certified, Fairtrade & Rainforest as well as Geographic Index Certification (Diyarma; Bantacut, 2019). The mass used for each of these torrefaction tests is approximately 200 g and the testing process (n) was repeated 5 times for each variation of the atmospheric medium used.

The characteristics of the air, Nitrogen (N_2), and Argon (Ar) used as the atmospheric media are presented in Table 1. It was discovered that the local atmospheric air has 78.08% N_2 , and 20.95% O_2 with very minimal content of Ar, CO_2 , $H_2O(g)$, and other gases. The inert gases, N_2 and Ar, used were both classified as industrial. The composition of N_2 in the cylinder was 99.998% with a very minimal mixture of impurities O_2 , $H_2O(g)$, and other gases. Meanwhile, the composition of Ar in the cylinder was greater than 99.9% with a very minimal mixture of impurities O_2 , $H_2O(g)$, and other gases. The dehydration, devolatilization, and decarbonization phases of the torrefaction process can all be impacted by impurities. On the outermost surface of the feedstock, hemicellulose and contaminants undergo first reactions. The exothermic process may be preceded or followed by a sequence of reactions and interactions with chemicals emerging from the feedstock. Additionally, impurities will impact the condensation process. The properties of the torrefaction's solid, liquid, and gaseous products will be impacted by impurities. The purpose of using both inert gases with low impurity levels is to reduce their impact on potential reactions during the torrefaction process.

Table 1: Gas specifications for the atmosphere media of the coffee bean torrefaction process used.

Specification	Atmospheric Media		
	Air	N ₂	Ar
Quality	Atmosphere air	Industrial grade	Industrial grade
Composition & Mixture Impurities	N ₂ : 78,08 %	N ₂ > 99,998 %	Ar > 99,9 %
	O ₂ : 20,95 %	O ₂ ≤ 2 ppm	N ₂ < 15 ppm
	Ar: 0,93 %	H ₂ O _(g) ≤ 3 ppm	O ₂ ≤ 10 ppm
	CO ₂ : 0,034 %	Hydrocarbons < 0.5 ppm	H ₂ O _(g) ≤ 10 ppm
	H ₂ O _(g) < 10 ppm	CO & CO ₂ < 1 ppm	Hydrocarbons < 0,5 ppm
Thermal Conductivity, (W/ m K)	0,02500	0,02583	0,01772
Density, (g/L)	1,29	1,251	1,784
Specific Heat, J/(mol·K)	29,07	29,124	20,85

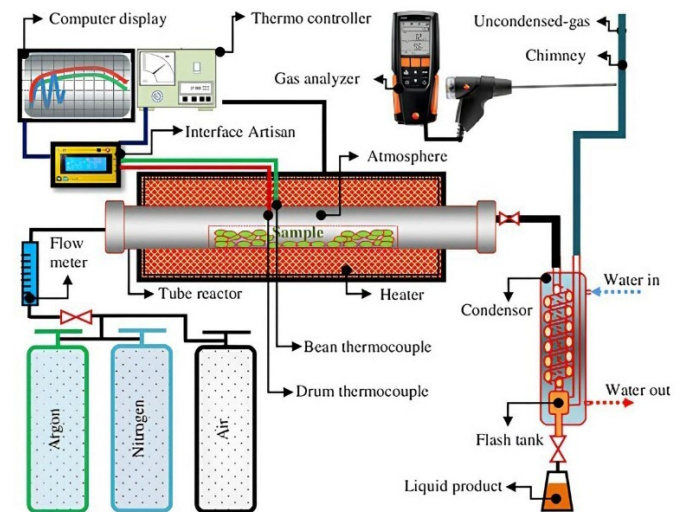
2.1 Fixed-bed coffee bean torrefaction

The torrefaction process was conducted using a fixed-bed torrefier as shown in Figure 1. The coffee beans were placed in a bed and put into a torrefier tube, after which the atmospheric medium was flowed into the 2 inch tube at a flow rate of 1 l/min, while the heater temperature was set at 235°C. For the three types of atmospheric media that were utilized, a flow rate of 1 l/min was used in order to maintain the flow in laminar conditions. According to earlier studies, laminar flow can lower pressure losses, maintain a steady temperature distribution, regulate mixing, and lower heat loss and efficiency (Li et al., 2021). The temperature is slightly higher than the peak exothermic temperature (230 °C) encountered during the hemicellulose depolymerization process (Chen; Kuo, 2011). Hemicellulose is the most degradable component of biomass. Hemicellulose is a polysaccharide built from sugar molecules attached by glycosidic bonds. This bond begins to break about 230-250 °C, resulting in smaller molecules known as hemicellulose depolymerization. In order to facilitate the hemicellulose depolymerization process, a temperature of 235 °C was selected. Although the prolonged process causes over-roasted beans, the temperature is not raised, and the coffee ought to be categorized as dark roasted. Despite the temperature variation in the heater, the temperature was not set lower, therefore the temperature of 235 °C was the appropriate choice in this study.

It is important to note that the temperature of the heater is the same as the ambient air when it was turned on but increased to 235±8 °C after 12 min and the heater was switched off after 60 min. The coffee beans entered the cooling process stage until the temperature reached 50 °C after 180 min.

The flue gas produced from the beginning of the torrefaction to the end of the cooling process flowed through a water-cooled condenser unit and flash tank at a temperature of 16±5 °C while the average temperature measured was 20.6 °C. It is important to note that all gas flowing through the condenser unit can be condensed while the uncondensed ones are passed through the chimney unit. The Testo meter 310 sensor was

placed in the chimney duct to measure the characteristics of the flue gases. Moreover, the uncondensed-gas flowing in the chimney was distinguished based on the variation of the air atmosphere, N₂, and Ar used for the torrefaction process.

**Figure 1:** Set-up fixed-bed torrefier of coffee beans.

The solid and liquid yields (Y) from the torrefaction and cooling process were determined using the equation (1). The symbol of m_p and m_r in the equation represents mass of product (kg) and mass of raw material (kg), respectively.

$$Y(\%) = \frac{m_p}{m_r} \times 100 \% \quad (1)$$

Meanwhile, the uncondensed-gas yield was determined based on the mass balance principle as indicated in the equation (2), the subscripts g , s , and l in the equation represent uncondensed-gas, solid, and liquid products, respectively.

$$Y_g (\%) = 100 \% - (Y_s + Y_l) \quad (2)$$

The uncondensed-gas yield was statistically analyzed with a 95% confidence level and a 5% or 0.05 margin of error. Since the yield data is expressed as a percentage, it can be categorized as a numeric data scale that satisfies the prerequisites for selecting a parametric test method. Because three different types of atmospheric media were employed in this test, the data acquired can be divided into three groups of unpaired data, prompting researchers to apply the one-way ANOVA method as a parametric method or the non-parametric Kruskal-Wallis method as an alternative.

The data must also be normal and homogenous, which can be determined using normality and homogeneity tests, respectively. The yield data are repeated five times for each of the three atmospheric media changes, and the Lilliefors and Shapiro Wilk normality analysis methods are used, but Shapiro Wilk is the most power for larger data set (Razali; Wah, 2011). Levene homogeneity tests, which were applied to the data, are a reliable technique that can be applied to both small and big data sets. The normality and homogeneity assumptions are accepted if the p value of the test findings is higher than the significance threshold (0.05); if it is lower, the assumptions are not.

If all of the conditions for the parametric test are met, the one-way ANOVA method can be used; however, if one of them is not met, a non-parametric method, Kruskal-Wallis, must be used. The post hoc test was used to continue the investigation since the statistical analysis revealed a substantial impact of atmospheric media variations, where $p < 0.05$. Both the LSD and Mann-Whitney methods are post hoc tests of one-way ANOVA and Kruskal-Wallis, respectively.

The p value of the test results is displayed in the table as well as the average value and its deviation for the analysis results using parametric statistical methods, while for non-parametric ones are the median, minimum, and maximum values. The p value of the post hoc test results is displayed as a footnote in the table.

2.2 Measurement of temperature versus time of torrefaction and cooling process

During the torrefaction and cooling processes, a pair of thermocouples are used to measure the temperature of the drum and beans. The drum temperature thermocouple sensor is configured so that it actually contacts the drum, whereas the bean temperature thermocouple sensor is designed to detect the temperature of the beans in the drum but accurately reflects the atmospheric media temperature inside the drum chamber. Both thermocouples are connected to the Artisan visual roaster scope as an interface as well as the Artisan 2.4.2 software on a computer to measure and record changes in drum and bean temperatures (°C) over time (min).

2.3 Measurement of temperature and CO emission of uncondensed-gas

The temperature data (°C) and CO emission (ppm) of uncondensed-gas were determined using a gas analyzer testometer series 310 sensor which was placed on the chimney as indicated in Figure 1. The device was also equipped with a small piston to suck some of the gas flowing in the chimney. Moreover, the gas flowing in a metal tube was used as the sample to be measured.

The uncondensed-gas temperature in the measuring instrument was termed the *fumi* temperature while the outside air temperature detected at the period is known as the *aria* temperature. It is important to note that *fumi* and *aria* are Italian terms for smoke and air, respectively. The average data for the three measurements were recorded every 7.5 minutes and this was conducted from the beginning of the torrefaction to the end of the cooling process when the temperature of the coffee beans reached 50°C. The data were recorded and tabulated for further analysis.

Different analyses were performed to determine the normal distribution of the uncondensed-gas temperature and CO emission data. Shapiro-Wilk was selected for the normality test technique based on the number of data ($9 \leq N \leq 50$) for the difference between the *fumi* to *aria* temperatures and CO emission for the three modifications of atmospheric media. Using this approach and data range, the results of data normality analysis have the highest level of validity (Razali; Wah, 2011).

3 RESULTS

3.1 Profile of coffee bean torrefaction temperature and cooling over time

Figure 2 illustrates the relationship between the temperature of the drum (ET) and the coffee beans (BT) (°C) over the torrefaction and cooling time (minutes) of the beans, taking into account variations in the air, N₂, and Ar atmospheric media. It shown that the temperature profile of the coffee bean torrefaction and cooling process is nearly identical between samples utilizing air, N₂, and Ar atmospheric media, in each three separated stages. In stage I, the coffee beans were started at room temperature and then progressively heated to the preset temperature of 235°C. The torrefaction process was stage II, while the cooling process was stage III.

ET temperature profile is greater than BT in stages I and II, but it falls below BT in stage III. The temperature profiles of ET and BT in stage II of the magnification section clearly distinguish between samples using oxidative air media and those using non-oxidative inert gases (N₂ and Ar).

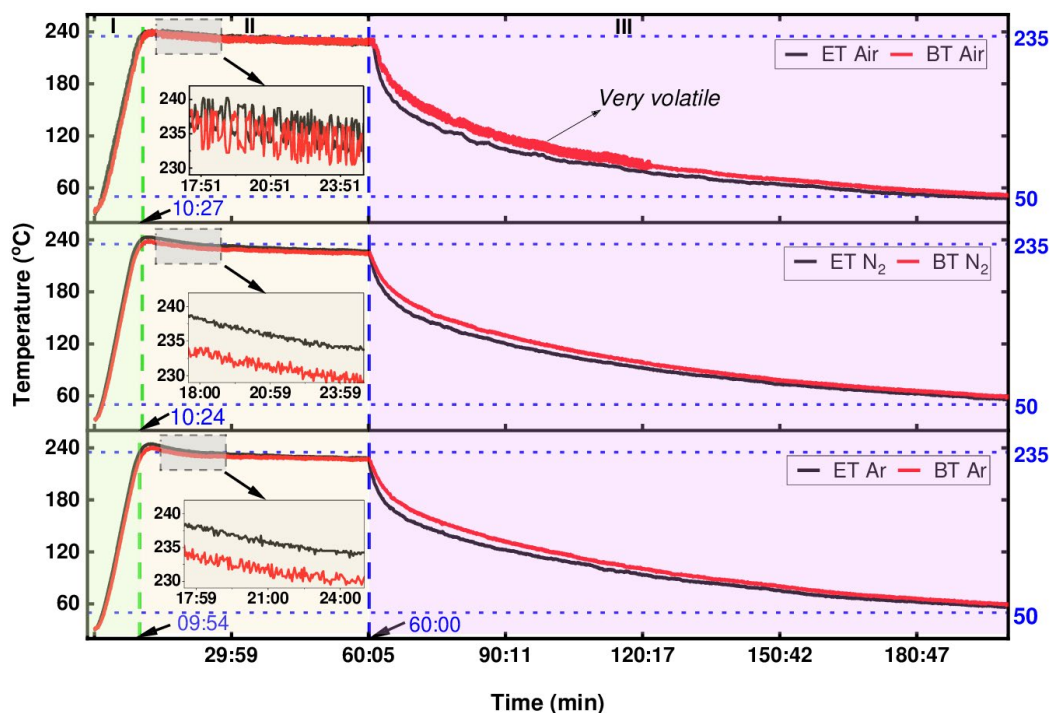


Figure 2: Temperature (°C) vs. time (min) of coffee bean torrefaction and cooling process with different atmospheric media (air, N₂, and Ar).

4 THE YIELD OF COFFEE BEAN TORREFACTION

The average yield of the solid, liquid, and uncondensed-gas products after the torrefaction process is presented in Figure 3. Solid and liquid yield products were obtained using Equation (1), meanwhile, the uncondensed-gas yield was obtained based on equation (2). Statistical analysis results of the uncondensed-gas yields of coffee bean torrefaction using air, N₂, and Ar atmospheric media were shown in Table 2.

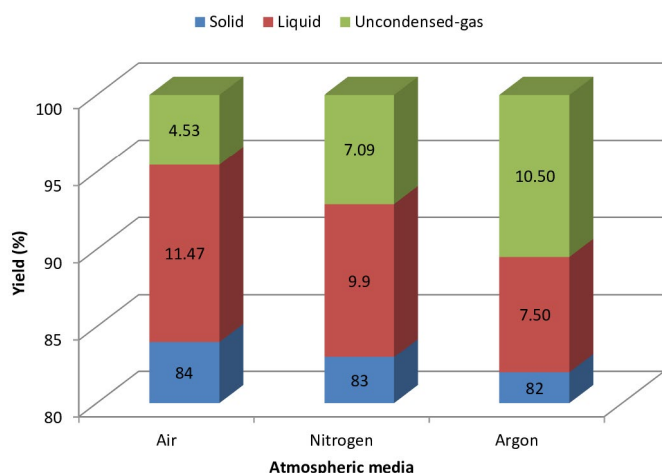


Figure 3: Average yields of solids, liquids, and uncondensed-gases during torrefaction in air, N₂, and Ar atmospheres.

Table 2: Statistical analysis results of the uncondensed-gas yields of coffee bean torrefaction using air, N₂, and Ar atmospheric media.

Atmosphere media	N	Uncondensed-gas yields (%)	
		One way ANOVA	
		Mean ± SD	P
Air	5	4.53 ± 2.7982	0.010
Nitrogen (N ₂)	5	7.09 ± 1.3782	
Argon (Ar)	5	10.5 ± 2.5125	

One way ANOVA test. LSD post hoc test: air versus N₂ p = 0.128; air versus Ar p = 0.003; N₂ Versus Ar p = 0.060.

The uncondensed-gas yield has normally distributed and homogenous data which can be tested statistically using ANOVA. The results showed a significant difference between the average yield of uncondensed-gas and variations in atmospheric media (p = 0.010). Moreover, the post hoc Least Significant Difference (LSD) test indicated a significant difference between the Ar and air media (p = 0.003).

4.1 The uncondensed-gas temperature distribution

The relationship between *fumi* and *aria* temperature (°C) to the time (min) of the uncondensed-gas produced through the application of air, N₂, and Ar atmospheric media were shown in Figure 4. The figure shows that the *fumi* temperature was increasing, specifically with the usage of N₂ and Ar media.

However, it decreased significantly with air after the 90th minute and slightly after the 155th minute but increased at the end of the cooling process. the insert table on the Figure 4 shows some descriptive data associated with the temperatures.

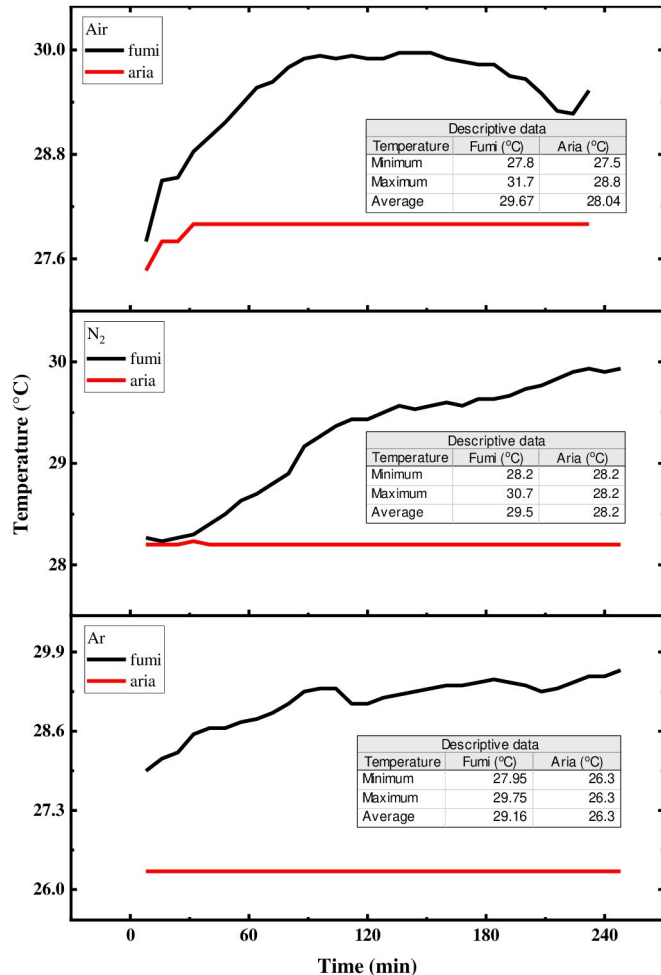


Figure 4: The relationship of *fumi* and *aria* temperatures with time for the exhaust gases from the coffee bean torrefaction at different variations of air, N₂, and Ar media.

The relationship between the *fumi* and *aria* temperatures difference (°C) with respect to the time (min) for the uncondensed-gas produced through the torrefaction process conducted using atmospheric air, N₂, and Ar were shown in Figure 5. It was observed that the difference between the *fumi* and *aria* temperatures due to the application of Ar is greater followed by air and N₂ media which increased with time

The statistical analysis test conducted showed that the difference between the *fumi* and *aria* temperatures with respect to time was not normally distributed ($p = 0.003$), therefore, the Kruskal-Wallis non-parametric test was performed. The results showed a significant difference in the mean temperature difference between *fumi* and *aria* for the three atmospheric media used ($p =$

0.000), as shown in Table 3. Moreover, the Post hoc Mann-Whitney test indicated there were significant differences between N₂ and Ar ($p = 0.000$), N₂ and air ($p = 0.001$), and Ar and air ($p = 0.000$).

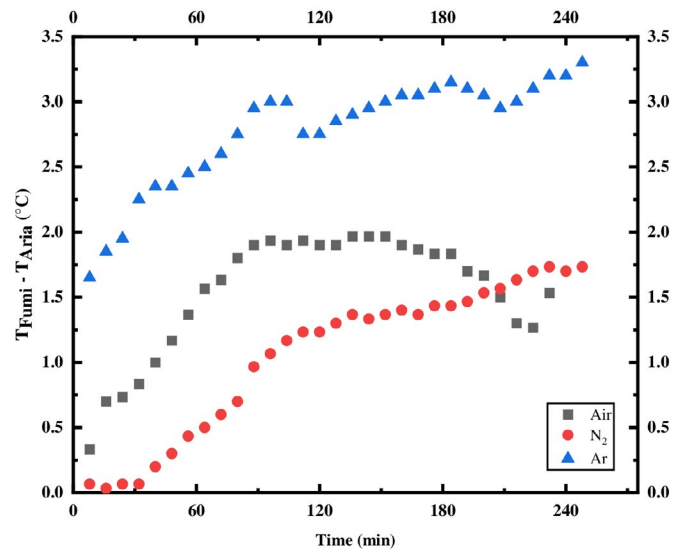


Figure 5: Relationship graph on the difference between the *fumi* and *aria* temperatures difference (°C) with respect to the time (min) for the uncondensed-gas produced during the coffee bean torrefaction using air, N₂, and Ar atmospheric media.

Table 3: Statical analysis result of uncondensed-gases temperature and CO emission of coffee bean torrefaction using air, N₂, and Ar atmospheric media.

Atmosphere Media	N	Fumi-aria temperature difference (°C)		CO emission (ppm)	
		Kruskal-Wallis		Kruskal-Wallis	
		Median (minimum-maximum)	p	Median (minimum-maximum)	P
Air	29	1.8 (0.3-2.9)	0.000*	186.3 (5.5-169.3)	0.000**
N ₂	35	1.4 (0.0-2.5)		42.7 (8.7-924.7)	
Ar	35	3 (1.65-3.45)		31.5 (5.5-818.5)	

* Kruskal-Wallis test. Mann-Whitney post hoc test: air versus N₂ $p = 0.001$; air versus Ar $p = 0.000$; N₂ versus Ar $p = 0.000$.

**Kruskal-Wallis test. Mann-Whitney post hoc test: air versus N₂ $p = 0.000$; air versus Ar $p = 0.000$; N₂ versus Ar $p = 0.07$.

4.2 The CO emission in the uncondensed-gas

Figure 6 shows a graph of the relationship between CO emission (ppm) and time (min) for uncondensed-gas produced from coffee bean torrefaction using air, N₂, and Ar. The results showed that the distribution of CO emission with the usage of air is higher compared to Ar and N₂.

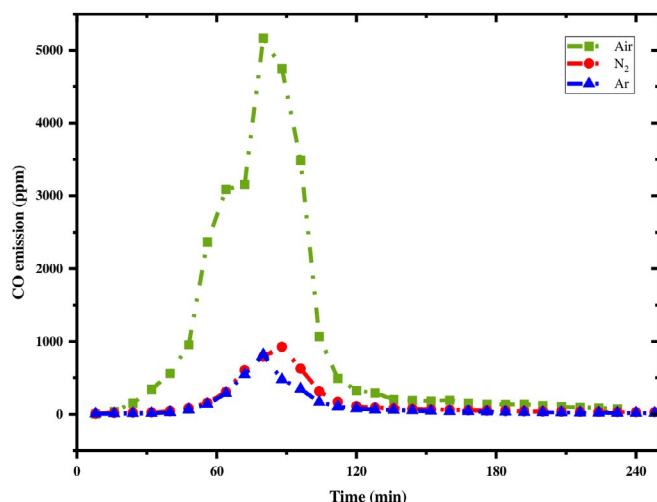


Figure 6: Relationship graph between CO emission (ppm) and time (min) for the uncondensed-gas produced during the coffee bean torrefaction using air, N₂, and Ar atmospheric media.

The statistical analysis conducted also indicated that the CO data were not normally distributed ($p = 0.000$), therefore, Kruskal-Wallis non-parametric test was performed. The results showed a significant difference in the mean levels of CO produced by the three atmospheric media used ($p = 0.000$), as shown in Table 3. The post hoc Mann-Whitney test also highlighted significant differences between N₂ and air ($p = 0.000$) and Ar and air ($p = 0.000$), but there was no significant variation between N₂ and Ar ($p = 0.07$).

5 DISCUSSION

5.1 Coffee bean torrefaction temperature and cooling over time of oxidative and non-oxidative atmospheric media

Figure 2 shows that stage I begins with the coffee beans at the same temperature as the ambient temperature and then rises sharply to temperatures above 235°C in 10.27, 10.24, and 9.54 minutes for air, N₂, and Ar, respectively. Exothermic reactions resulting from secondary char-volatile processes allow temperatures to rise above the torrefaction point (Bates; Ghoniem, 2013), that is related to hemicellulose depolymerization. The heat generated cannot be transported fast due to the low Biot number.

In the stage II, the torrefaction process takes 60 minutes at 235±8°C. At the commencement of the stage II, the temperature profile exceeds 235°C, where the char-volatile reaction is still taking place. After 30 minutes of torrefaction, the temperature often falls below 235°C. This is assumed to be attributable to hemicellulose degradation and should indicate that the torrefaction process for coffee beans is complete

(Bergman et al., 2005), as the char-volatile reaction has ceased. Stage III is a cooling process in which the temperature decreases rapidly at the beginning of the process and then slopes and ends when BT reaches a temperature of 50 °C in 180 min.

The temperature profiles of ET and BT in stage II of the magnification section of Figure 2 clearly distinguish between samples using oxidative air media and those using non-oxidative inert gases (N₂ and Ar). It can be noted that the process temperature profile for samples employing air medium is quite fluctuating, intersecting between ET and BT as opposed to inert gas, which is clearly separated. The BT temperature profile for samples that employ air as the atmospheric medium remains quite fluctuating from the beginning of stage III until the middle of the cooling process, however there is no longer an intersection with the ET profile.

This fluctuation process is assumed to be caused by an exothermic oxidation reaction due to the oxygen concentration in the air, which is used as the torrefaction atmospheric fluid (Rousset et al., 2012), (Joshi et al., 2015). Even after the char-volatile exothermic reaction is over, the exothermic oxidation process continues. This reaction causes the temperature increase, which is detected by the thermo controller, which stops supplying heat to the reactor tube and causes the temperature to fall to the minimal limit, prompting the thermo controller to re-connect to supply heat.

This phenomena of temperature profile differences between those employing oxygen and inert gas is in line with prior research, which is torrefaction performed on poplar wood at 250°C for 60 min, with variations in oxygen levels in the atmospheric media utilized. The test results reveal that torrefaction utilizing atmospheric media with increased oxygen levels leads in a higher core temperature distribution profile graph over time (Basu et al., 2013), This is consistent with prior research findings (Rousset et al., 2012).

5.2 The effect of atmospheric media variation of torrefaction on uncondensed-gas yield

The average yield of the solid, liquid, and uncondensed-gas products after the torrefaction process is presented in Figure 3. It is important to note that solid and liquid yield produced through air torrefaction were observed to be higher, and then followed by N₂ and Ar. Meanwhile, the uncondensed-gas yield from Ar atmosphere media was observed to be higher followed by N₂ and air. This means the yield is inversely proportional to the findings for the liquid product which was in the form of liquid smoke. Therefore, the condensation of more exhaust gas is expected to lead to little uncondensed ones and vice versa.

The high concentration of N₂ gas in the atmospheric medium is believed to have the ability of inhibiting the evaporation process as well as the evolution of N elements from the raw materials used for the torrefaction. This agrees

with the findings of previous research that atmospheric media rich in N elements produced solid products with high N content through biomass torrefaction (Ma et al., 2019), (Xu et al., 2020). A similar phenomenon is expected with the quantity and quality of the liquid smoke and uncondensed-gas produced in the torrefaction of coffee beans using N_2 in this research.

The high level of O_2 in air media is expected to have much effect on the decomposition reaction process. The coffee bean torrefaction conducted using air is expected to decompose due to an oxidation reaction but a contrasting result was recorded in the test and this is associated with the fact that the process was conducted at a lower temperature. This is in line with the relatively small effect of oxygen reported on biomass torrefaction at low temperatures (Zhang et al., 2019), (Sun et al., 2020), (Hisham; Uemura; Tazli, 2016). This is also related to the thermo controller function, which prevents heat and process temperature from increasing further, hence preventing excessive oxidation processes.

It was further reported that the torrefaction conducted using oxidative media led to oxidation reactions on the outer surface of the biomass (Barskov et al., 2019). A similar trend was observed in the application of air as media where oxidation was discovered to have occurred on the outer surface of the coffee bean as indicated by the silver skin. This subsequently affected several characteristics of the main and uncondensed-gas products as indicated by their difference from those produced using inert gases such as N_2 and Ar as atmospheric media.

The decomposition of torrefied coffee beans associated with the inert gas atmosphere is mainly due to the decarboxylation or cracking events and decarbonylation or reforming reactions. Cracking is defined as the breaking of a large molecule into smaller ones through heating without O_2 (Wang et al., 2017) and also has the ability to produce a carboxyl group ($-COOH$). The decarbonylation reaction causes the formation of a carbonyl group ($C=O$). These elements are both derived from the thermal degradation of hemicellulose. Meanwhile, the coffee bean torrefaction process using atmospheric media containing oxidative elements (O_2) usually leads to an oxidation reaction of the carboxyl and carbonyl groups. It is also important to note that incomplete combustion normally leads to the formation of CO while complete combustion forms CO_2 (Shibamoto, 2015). Moreover, the formation of high CO, CO_2 , and H_2O due to the combustion of high levels of O_2 in atmospheric media is expected to cause a decrease in the levels of CH_4 formed (Kung et al., 2019).

The use of air, N_2 , and Ar atmosphere media containing different main contents and minimal gaseous impurities produced different products from the coffee bean torrefaction. It was observed that the mixture of $H_2O_{(g)}$ impurities in these media, even at minimal content, contributed to the decomposition process at the early stages of dehydration

which involved the evaporation of $H_2O_{(l)}$ contained in coffee beans. This is due to the fact that lesser content of $H_2O_{(g)}$ levels usually leads to faster $H_2O_{(l)}$ evaporation during the early stages of decomposition. Moreover, the hydrocarbons, CO, and CO_2 contents were also perceived to have influenced the decomposition process at the devolatilization stage and this further affect the characteristics of the uncondensed-gas.

The differences in the characteristics of the atmospheric media were also observed to have affected the condensation process of liquid smoke produced during the torrefaction. This was indicated by the relatively low conductivity and heat capacity of the Ar media used which was perceived to have affected the condensation process and led to the production of lesser liquid smoke compared to air and N_2 . Moreover, even though N_2 has slightly higher conductivity and heat capacity than air, its density is smaller and this is the reason the liquid smoke produced using air was higher.

ANOVA can be used to statistically test the uncondensed-gas yield's regularly distributed ($p > 0.05$) and homogeneous ($p > 0.05$) data. The results showed a significant difference between the average yield of uncondensed-gas and variations in atmospheric media ($p = 0.010$), as shown in Table 2. Moreover, the post hoc Least Significant Difference (LSD) test indicated a significant difference between the Ar and air media ($p = 0.003$).

5.3 The effect of atmospheric variations on temperature of uncondensed-gas

The determination of the temperature to be used for the thermal treatment of coffee beans is very important in the roaster machine used as the torrefaction device. Manufacturers usually recommend a specific temperature standard for their roaster designs and this means the requirements are very different. Moreover, the focus is not only on the profile temperature including the coffee bean and drum but also on those associated with the exhaust gas. It is important to note that the temperature profiles of the exhaust gas are different but the thermal process is the same, thereby making it easy to compare the products from different roasters (Macheiner; Schmidt; Mayer, 2021). The monitoring of exhaust gases is more effective when the release process is not only related to the type of compound and time but also the temperature and this is required to ensure standardization and comparability (Lebouf; Aldridge, 2019). The temperature to be observed is not for only the process but also for the exhaust gas and ambient air.

Several industrial-scale roasters usually recirculate their exhaust gases for effective energy use (Schenker; Rothgeb, 2017). This is also possible in the coffee bean torrefaction process, specifically when expensive inert gas is used. The gas normally has a higher temperature potential than before and the recirculation also brings back the previously

uncondensed generated volatiles. This means the design of the scrubber technology to recover the inert gas used requires considering the temperature of the exhaust gas. This shows that the temperature of the exhaust gas also needs to be understood in addition to those associated with the torrefaction process. Furthermore, the clarity of the parameters for the torrefaction process is necessary for subsequent comparison with other designs.

The temperature profile of exhaust gas is usually determined through two parameters which include the *fumi* (smoke) and *aria* (air) due to the fact that the difference between them normally provides the potential for natural draft effects on the chimney with subsequent influence on the overall process system. Figure 4 shows that the *fumi* temperature was increasing, specifically with the usage of N₂ and Ar media. However, it decreased significantly with air after the 90th minute and slightly after the 155th minute but increased at the end of the cooling process.

Meanwhile, the insert table on the Figure 4 shows some descriptive data associated with the temperatures. *Aria* temperature is defined as the ambient air temperature which was measured through the instrument sensor placed on the chimney. The average values measured in the test samples with air and N₂ media were found to be almost the same at 28.04 and 28.2°C, respectively, but a reduced value of 26.3°C was recorded for Ar. The *aria* temperature value was observed to be strongly influenced by environmental conditions and not by the atmospheric media used as indicated by the values recorded for all the variations which tend to be constant.

Figure 5 shows that the difference between the *fumi* and *aria* temperatures due to the application of Ar is greater followed by air and N₂ media which increased with time. The difference between the *fumi* and *aria* temperatures contributes to the variations recorded in the flue gas pressure passing through the chimney and this subsequently influenced the natural draft of the gas. This is in line with the previous research that a greater difference between *fumi* and *aria* temperature influences gas pull (Faisal et al., 2018). Therefore, it is estimated that the uncondensed-gas pull in the coffee bean torrefaction process conducted using Ar atmosphere media is greater compared to air and N₂ which increased with time. This means the application of different atmospheric media influenced the temperature profile as shown in Figures 4 and 5 and this tends to affect the torrefaction and condensation process.

The difference in the *fumi* temperature profile with the usage of air atmospheric medium in the torrefaction process is probably due to the oxidation between the volatiles of the coffee beans and the oxygen content in the air compared to the profile of the inert gas including N₂ and Ar. Meanwhile, the differences in the *fumi* and *aria* temperature profiles for the uncondensed-gas produced using N₂ and Ar media

were perceived to have led to variations in the results of the torrefaction process. This means environmental conditions seem to influence the torrefaction process of the coffee bean. Moreover, the quality and quantity of liquid smoke samples produced from unreactive inert gas atmosphere media including N₂ and Ar were observed to be different. The higher difference between the *fumi* and *aria* temperatures for the uncondensed-gas produced using Ar compared to N₂ was believed to have influenced the thermal degradation process and the condensation of liquid smoke produced. This is in line with the findings of previous research that there are variations in the results of the thermal process applied to coffee beans using air media as well as different inert gases which include N₂ and helium. The reason for this variation is unknown and no data showed the ambient and uncondensed-gas temperature profile (Moon; Shibamoto, 2010).

The statistical analysis test revealed that the variation in *fumi* and *aria* temperatures over time was not normally distributed ($p = 0.003$), negating the requirement for a homogeneity test. The non-parametric Kruskal-Wallis test was thus run. The results showed a significant difference in the mean temperature difference between *fumi* and *aria* for the three atmospheric media used ($p = 0.000$), as shown in Table 3. Moreover, the Post hoc Mann-Whitney test indicated there were significant differences between N₂ and Ar ($p = 0.000$), N₂ and air ($p = 0.001$), and Ar and air ($p = 0.000$).

Air-based samples and inert gas (N₂ and Ar)-based samples have different amounts of data. Although the data collection time is set at 7.5 minutes, it actually takes longer for samples that use air. Compared to inert gas, less temperature data is gathered for samples employing air media from the beginning to the end of the procedure. The analysis's findings, however, demonstrate that the data imbalance is not an issue and has no consequence on the statistical analysis's findings. The analysis's findings are in line with those of the other two important inert gas data. The findings of the statistical analysis are regarded as valid since they support the distinctive pattern displayed by the temperature difference graphs of *fumi* and *aria* uncondensed gas.

5.4 The effect of atmospheric variations on CO emission in the uncondensed-gas

Figure 6 shows sharp peaked from the first 10 minutes, experienced a constant distribution shortly after the 60th to 70th minute when the torrefaction process ended and the cooling process started, increased again very sharply to reach its maximum at the 75th minute, declined drastically to the 110th minute, and slowly thereafter until the end of the cooling process.

It was discovered that the distribution graphs of the CO emission (ppm) against time (min) for uncondensed-gas

produced using N₂ and Ar media were close at the initial 75 minutes with the Ar observed to have reached its maximum value. However, a clear difference was indicated between 75-120 minutes with N₂ reaching its maximum peak at 95 minutes. This is associated with the variations in the characteristics of these two inert gases such as the specific capacity, thermal conductivity, density, or others that need to be studied further. After the 120th minute, the two graphs were close again and continue to slope to the end of the process.

Figure 6 also shows that the CO emission tends to increase as the temperature increases and vice versa, and this was observed in all the atmospheric media used. The CO from uncondensed-gas is usually estimated to be constant for processes conducted using inert gases because the CO was found in impurities. However, the inability of the inert gas to react led to the assumption that the CO gas is different from the impurities due to the volatile combustion experienced in the torrefaction process using the two inert gas media. Meanwhile, the use of air was perceived to have allowed CO gas from volatile combustion and also from incomplete combustion of fixed carbon from the outer layer of coffee beans as indicated by the silver skin. This study's findings are consistent with prior studies, which found that oxygen only promotes dehydration and decarboxylation reactions, resulting in oxidation (combustion) for the torrefaction process at low temperatures and a low H/C and O/C ratio (Rousset et al., 2012), (Jadsadajerm et al., 2024).

It was also discovered that 0.8 kg/ton or 0.08% CO of coffee beans was produced from the continuous roasting process, 1535 ppm or approximately 0.15% of CO gas was measured in a drum roaster (Sawitri et al., 2019), and 5207 ppm from 1 kg of coffee beans (Rim; Kim, 2020). Moreover, CO was also observed to have been formed at the same time as carbon dioxide and started accumulating when the first crack occurred in the 6th minute up to the second crack in the 18th minute when the oil migrated to the coffee surface (Yergenson; Aston, 2020). The phenomena reported concerning the variations of atmospheric media in the coffee bean torrefaction process are in line with the findings of several previous researches.

CO gas is a very dangerous substance in the environment and for human respiration, specifically for workers in the coffee bean processing industry, despite the possible benefits (Olas, 2014), for example, it might be converted into fuel (Müller et al., 2024), (Ngoc Ha et al., 2018), (Hasibuan; Setiawan; Faisal, 2024) or other important chemicals. The findings showed that the application of inert gases as atmospheric media for the thermal processing of coffee beans was able to reduce CO gas exposure compared to the utilization of air. However, there is a need for further research on the purification of inert gas from uncondensed-gas and their recirculation to ensure a continuous coffee bean torrefaction process considering the

high cost of these gases. The inert gas generation process also produces CF, which should be considered while selecting the process to be carried out.

The statistical analysis conducted also indicated that the CO data were not normally distributed ($p = 0.000$) negating the requirement for a homogeneity test., therefore, Kruskal-Wallis non-parametric test was performed. The results showed a significant difference in the mean levels of CO produced by the three atmospheric media used ($p=0.000$), as shown in Table 3. The post hoc Mann-Whitney test also highlighted significant differences between N₂ and air ($p = 0.000$) and Ar and air ($p = 0.000$), but there was no significant variation between N₂ and Ar ($p = 0.07$).

Similar to the temperature data, the uncondensed-gas CO emission data for air media samples differs from that for inert gas media. It takes a non-uniform amount of time to manually switch between temperature and CO emissions on one of the testo tool's displays. The amount of data collected was smaller because the air medium took a little longer than 7.5 minutes. Nonetheless, logical and valid conclusions from the statistical analysis supported the graph's trend. The findings of the statistical test are in line with the graph created by the CO emission data from the air sample, which is significantly above the inert gas. Both inert gases and air data show consistent post-hock analysis results. Valid post-hock results between the two inert gases are also indicated by the CO gas emission graph's unique trend of measurement results. The uncondensed gas samples' CO emission graphs with N₂ and Ar atmospheric medium show little variation.

6 CONCLUSIONS

The torrefaction temperature profile using air medium fluctuates due to exothermic oxidation from oxygen, unlike inert gases which are more stable. Atmospheric medium variation significantly affects uncondensed-gas yield, CO emission and temperature differences among N₂, Ar and air. Air causes higher fluctuations and CO emission, while inert gases reduce them. Torrefaction, as an alternative to roasting produces solids as main products and enhances sustainability, reduce carbon footprint, and support coffee trade and farmer welfare through environmentally friendly processing.

7 AUTHORS' CONTRIBUTION

Conceptual Idea: Faisal, F.; Khairil, K.; Husni H.; Methodology design: Faisal, F.; Khairil, K.; Husni H.; Data collection: Faisal, F.; Data analysis and interpretation: Faisal, F.; Cut, S.N, Yusya A., and Writing and editing: Faisal, F; Cut, S.N.; Khairil, K.; Yusya. A.

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9 DATA AVAILABILITY STATEMENT

Data available upon request to authors.

10 REFERENCES

- BARRIOS-RODRÍGUEZ, Y. F. et al. Rational design of technologies for the mitigation of neo-formed contaminants in roasted coffee. **Trends in Food Science & Technology**, 120:223-235, 2022.
- BARSKOV, S. et al. Torrefaction of biomass: A review of production methods for biocoal from cultured and waste lignocellulosic feedstocks. **Renewable Energy**, 142:624-642, 2019.
- BASU, P. et al. Effect of oxygen presence in torrefier. **Journal of the Energy Institute**, 86(3):171-176, 2013.
- BATES, R. B.; GHONIEM, A. F. Biomass torrefaction: Modeling of reaction thermochemistry. **Bioresource Technology**, 134:331-340, 2013.
- BERGMAN, P. C. A. et al. **Torrefaction for biomass co-firing in existing coal-fired power stations**. Biocoal. 2005. 71p.
- BIRKENBERG, A. et al. The potential of carbon neutral labeling to engage coffee consumers in climate change mitigation. **Journal of Cleaner Production**, 278:123621, 2021.
- CHEN, W.-H.; KUO, P.-C. Torrefaction and co-torrefaction characterization of hemicellulose, cellulose and lignin as well as torrefaction of some basic constituents in biomass. **Energy**, 36(2):803-811, 2011.
- DA COSTA, D. S. et al. Thermal contaminants in coffee induced by roasting: A Review. **International Journal of Environmental Research and Public Health**, 20(8):5586, 2023.
- DAS, P. P.; DUARAH, P.; PURKAIT, M. K. Fundamentals of food roasting process. In: JAFARI, S. M. **High-temperature processing of food products**. [s.l.] Elsevier, p. 103-130, 2023.
- DIYARMA, I.; BANTACUT, T. Assessment of environmental impact of the gayo arabica coffee production by wet process using Life Cycle Assessment. **Acta Universitatis Cinbinesis, Series E: Food Technology**, 23:1, 2019.
- ECHT, H. et al. Characterization of naturally occurring alpha-diketone emissions and exposures at a coffee roasting facility and associated retail café. **Annals of Work Exposures and Health**, 65(6):715-726, 2021.
- FADRI, R. A. et al. Review proses penyangraian kopi dan terbentuknya akrilamida yang berhubungan dengan kesehatan. **Journal of Applied Agricultural Science and Technology**, 3(1):129-145, 2019.
- FAISAL, F. et al. The effect of atmospheric media variation on liquid characteristics of torrefied coffee beans. **Journal of Analytical and Applied Pyrolysis**, 168:105799, 2022.
- FAISAL, F. et al. The effect of atmospheric media variations on the characteristics of torrefied coffee beans. **Results in Engineering**, 17:100826, 2023
- FAISAL, F. et al. Experimental study of the chimney height variation against double pots biomass stove performance. **Makara Journal of Technology**, 21(3):109, 2018.
- FREITAS, V. V. et al. Coffee: A comprehensive overview of origin, market, and the quality process. **Trends in Food Science & Technology**, 146:104411, 2024.
- FULLER, K.; GREBITUS, C. Consumers' preferences and willingness to pay for coffee sustainability labels. **Agribusiness**, 39(4):1007-1025, 2023.
- HASIBUAN, R.; SETIAWAN, A.; FAISAL, F. Utilization of syngas as co-firing fuel for carbonization of arabica coffee pulp. **Journal of Engineering and Technological Sciences**, 56(6):771-780, 2024.
- HASSARD, H. A. et al. Product carbon footprint and energy analysis of alternative coffee products in Japan. **Journal of cleaner production**, 73:310-321, 2014.
- HAWLEY, B.; COX-GANSER, J. M.; CUMMINGS, K. J. Carbon monoxide exposure in workplaces, including coffee processing facilities. **American journal of respiratory and critical care medicine**, 196(8):1080-1081, 2017.
- HISHAM, S. M.; UEMURA, Y.; TAZLI, A. M. Effects of temperature and concentration of Oxygen on torrefaction of empty fruit bunches. **Journal of the Japan Institute of Energy**, 95(12):1110-1114, 2016.
- JADSADAJERM, S. et al. Influence of oxygen concentration on torrefaction of Leucaena: gas formation rates and chemical properties analysis. **Biomass Conversion and Biorefinery**, p. 1-11, 2024.

- JOSHI, Y. et al. Packed-bed torrefaction of bagasse under inert and oxygenated atmospheres. **Energy & Fuels**, 29(8):5078-5087, 2015.
- KLJAJIC, M.; ANDJELKOVIC, A.; GVOZDENAC, D. Viability analysis of heat recovery solution for industrial process of roasting coffee. **Thermal Science**, 20: 623-637, 2016.
- KRISHNAN, S. Sustainable coffee production. In: SHUGART, H. H **Oxford research encyclopedia of environmental science**. [s.l.] Oxford University Press, p. 1-29, 2017.
- KUNG, K. S. et al. Parametric analysis of torrefaction reactor operating under oxygen-lean conditions. **Energy**, 181:603-614, 2019.
- LEBOUF, R. F.; ALDRIDGE, M. Carbon monoxide emission rates from roasted whole bean and ground coffee. **Journal of the Air & Waste Management Association**, 69(1):89-96, 2019.
- LI, X. et al. Effect of oxidative torrefaction on high temperature combustion process of wood sphere. **Fuel**, 286:119379, 2021.
- LYONS, C.; TURCHI, C.; GRATSON, D. **Solving widespread low-concentration VOC air pollution problems**: Gas-phase photocatalytic oxidation answers the needs of many small businesses. [s.l.] National Renewable Energy Lab. (NREL), Golden, CO (United States), p. 1-12, 1995.
- MA, Z. et al. N-doping of biomass by ammonia (NH₃) torrefaction pretreatment for the production of renewable N-containing chemicals by fast pyrolysis. **Bioresource Technology**, 292:122034, 2019.
- MACHEINER, L.; SCHMIDT, A.; MAYER, H. K. A novel basis for monitoring the coffee roasting process: Isomerization reactions of 3-caffeoylquinic and 4-caffeoylquinic acids. **LWT**, 152:112343, 2021.
- MILANI, M.; MONTORSI, L.; TERZI, S. Numerical analysis of the heat recovery efficiency for the post-combustion flue gas treatment in a coffee roaster plant. **Energy**, 141:729-743, 2017.
- MOON, J.-K.; SHIBAMOTO, T. Formation of volatile chemicals from thermal degradation of less volatile coffee components: quinic acid, caffeic acid, and chlorogenic acid. **Journal of Agricultural and Food Chemistry**, 58(9):5465-5470, 2010.
- MÜLLER, A. V et al. Reduction of CO to methanol with recyclable organic hydrides. **Journal of the American Chemical Society**, 146(15):10524-10536, 2024.
- NAB, C.; MASLIN, M. Life cycle assessment synthesis of the carbon footprint of Arabica coffee: Case study of Brazil and Vietnam conventional and sustainable coffee production and export to the United Kingdom. **Geo: Geography and Environment**, 7(2):e00096, 2020.
- NEWTON, J. Carbon monoxide exposure from coffee roasting. **Applied Occupational and Environmental Hygiene**, 17(9):600-602, 2002.
- NGOC HA, N. et al. Conversion of carbon monoxide into methanol on alumina-supported cobalt catalyst: Role of the support and reaction mechanism-a theoretical study. **Catalysts**, 9(1):6, 2018.
- NISHIMURA, F.; ABE, S.; FUKUNAGA, T. Carbon monoxide poisoning from industrial coffee extraction. **JAMA**, 290(3):334, 2003.
- OLAS, B. Carbon monoxide is not always a poison gas for human organism: Physiological and pharmacological features of CO. **Chemico-Biological Interactions**, 222:37-43, 2014.
- PASCUCCI, F. The export competitiveness of Italian coffee roasting industry. **British Food Journal**, 120(7):1529-1546, 2018.
- RAZALI, N. M.; WAH, Y. B. Power comparisons of shapiro-wilk, kolmogorov-smirnov, lilliefors and anderson-darling tests. **Journal of Statistical Modeling and Analytics**, 2(1):21-33, 2011.
- RIM, K.-T.; KIM, S.-J. A toxicogenomics study of two chemicals in coffee roasting process. **Molecular & Cellular Toxicology**, 16(1):25-38, 2020.
- RONDONI, A.; GRASSO, S. Consumers behaviour towards carbon footprint labels on food: A review of the literature and discussion of industry implications. **Journal of Cleaner Production**, 301:127031, 2021.
- ROUSSET, P. et al. Biomass torrefaction under different oxygen concentrations and its effect on the composition of the solid by-product. **Journal of Analytical and Applied Pyrolysis**, 96:86-91, 2012.
- SAWITRI, K. N. et al. Integration of gas sensors as an exhaust gas monitoring device from green roasting process of various coffee beans. **IOP Conf. Series: Journal of Physics: Conference Series**, 1282:012024, 2019.
- SCHENKER, S.; ROTHGEB, T. The roast-Creating the Beans' signature. In: FOLMER, B. (ed), **The craft and science of coffee**. Academic Press, Elsevier, p. 245-271, 2017.

- SHIBAMOTO, T. Volatile chemicals from thermal degradation of less volatile coffee components. FREEDY, V. R.; PATEL, V. **Coffee in health and disease prevention**. Academic Press, [s.l.] Elsevier, p. 129-135, 2015.
- SRUTHI, N. U. et al. An overview of conventional and emerging techniques of roasting: Effect on food bioactive signatures. **Food Chemistry**, 348:129088, 2021.
- SUN, Y. et al. Effect of torrefaction temperature and O₂ concentration on the pyrolysis behaviour of moso bamboo. **BioResources**, 15(3):6344-6370, 2020.
- TAMRU, S.; MINTEN, B. Value addition and farmers: Evidence from coffee in Ethiopia. **PLOS ONE**, 18(1):e0273121, 2023.
- TEIXEIRA, H. M. et al. How to quantify the impacts of diversification on sustainability? A review of indicators in coffee systems. **Agronomy for Sustainable Development**, 42(4):62, 2022.
- TSAI, W.-H.; LEE, K.-H.; HUANG, C.-C. Energy efficiency and carbon emission reduction in coffee roasting: Approach of Activity-Based Costing (ABC) Methodology. **Energies**, 18(5):1018, 2025.
- VARMA, D. R.; MULAY, S.; CHEMTOB, S. Carbon monoxide: from public health risk to painless killer. In: GUPTA, R. **Handbook of toxicology of chemical warfare agents**. Academic Press, Elsevier, p. 271-292, 2009.
- WANG, S. et al. Lignocellulosic biomass pyrolysis mechanism: A state-of-the-art review. **Progress in Energy and Combustion Science**, 62:33-86, 2017.
- WIBOWO, J. W. et al. A review of a smart coffee roaster: electronics, design, and artificial intelligence. **IOP Conference Series: Earth and Environmental Science**, 1116(1):012011, 2022.
- XU, L. et al. Recent advances of producing biobased N-containing compounds via thermo-chemical conversion with ammonia process. **Energy & Fuels**, 34(9):10441-10458, 2020.
- YERGENSON, N.; ASTON, D. E. Monitoring coffee roasting cracks and predicting with in situ near-infrared spectroscopy. **Journal of Food Process Engineering**, 43(2):e13305, 2020.
- ZHANG, C. et al. Oxidative torrefaction of biomass nutshells: Evaluations of energy efficiency as well as biochar transportation and storage. **Applied Energy**, 235:428-441, 2019.
- ZHAO, S. et al. Reducing carbon footprint of typical coffee consumption from the whole lifecycle viewpoint. **Environmental Impact Assessment Review**, 106:107476, 2024.