

Impact of extremely low frequency magnetic field-assisted fermentation on Arabica coffee caffeine content

[Pengaruh fermentasi berbantuan medan magnet frekuensi sangat rendah terhadap kandungan kafein biji kopi arabika]

Najma Zahiroh Fauziah¹ and Sudarti^{2*}

¹ Physics Education, Faculty of Teacher Training and Education, University of Jember, East Java, Indonesia

² Doctoral Program in Science Education, University of Jember, East Java, Indonesia

* Corresponding author email: sudarti.fkip@unej.ac.id

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ABSTRACT

Arabica coffee possesses a superior flavor profile; however, its high caffeine content necessitates an eco-friendly decaffeination method. This study analyzed the reduction of caffeine levels, fermentation pH, bean pH, and density through wet fermentation assisted by an Extremely Low Frequency (ELF) magnetic field. A 3×2 factorial design was applied using variations in magnetic field intensity (control, 300 μ T, and 500 μ T) and contact times (30 and 60 minutes). The fermentation process was carried out for 20 hours using tape yeast as a starter. Measurements of fermentation pH values were conducted periodically every 5 hours, which was then followed by the characterization of bean pH, density, and caffeine levels. The results showed that fermentation pH and bean pH values decreased, accompanied by an increase in density values; however, these changes were not significantly different among treatment groups (p -value > 0.05). Conversely, a statistically significant decrease in caffeine levels was observed. The best treatment was obtained with magnetic field exposure at 300 μ T for 30 minutes, resulting in a caffeine content of 0.0234%, or a 28.9% reduction from the negative control value (0.0329%). In conclusion, ELF magnetic field exposure at specific intensities and contact times was proven to optimize fermentation to effectively degrade caffeine levels. Future research is recommended to combine ELF magnetic field exposure with specialized microbial consortia or extend the duration of the fermentation process.

Keywords: arabica coffee, caffeine, ELF magnetic field, fermentation

ABSTRAK

Kopi Arabika memiliki profil rasa yang unggul, namun kadar kafeinnya yang tinggi memerlukan metode dekafeinasi yang ramah lingkungan. Penelitian ini menganalisis penurunan kadar kafein, pH fermentasi, pH biji, dan densitas melalui fermentasi basah berbantuan medan magnet Extremely Low Frequency (ELF). Rancangan faktorial 3×2 diterapkan menggunakan variasi intensitas medan magnet (kontrol, 300 μ T, dan 500 μ T) serta waktu kontak (30 dan 60 menit). Proses fermentasi dilakukan selama 20 jam dengan menggunakan ragi tape sebagai starter. Pengukuran nilai pH fermentasi dilakukan secara berkala setiap 5 jam, yang kemudian diikuti dengan karakterisasi pH biji, densitas, serta kadar kafein. Hasil penelitian menunjukkan bahwa nilai pH fermentasi dan pH biji mengalami penurunan yang disertai dengan peningkatan nilai densitas; akan tetapi, perubahan tersebut tidak berbeda signifikan antarkelompok perlakuan (p -value > 0,05). Sebaliknya, penurunan kadar kafein yang signifikan secara statistik berhasil diamati. Perlakuan terbaik diperoleh pada paparan medan magnet 300 μ T selama 30 menit, menghasilkan kadar kafein sebesar 0,0234%, atau tereduksi 28,9% dari nilai kontrol negatif (0,0329%). Kesimpulannya, paparan medan magnet ELF pada intensitas dan waktu kontak tertentu terbukti mengoptimalkan fermentasi untuk mendegradasi kadar kafein secara efektif. Penelitian berikutnya disarankan untuk menggabungkan paparan medan magnet ELF dengan konsorsium mikroba khusus atau memperpanjang durasi waktu proses fermentasi tersebut.

Kata kunci: fermentasi, kafein, kopi Arabika, medan elektromagnetik ELF.

Introduction

Coffee is one of the leading global commodities with high economic value and is the most widely consumed beverage worldwide (Jaworska & Majchrzak, 2025). In Indonesia, coffee consumption continues to exhibit significant growth, with domestic consumption reaching 5 million 60-kg bags in 2020 (Adithia & Jaya, 2021). Among commercially cultivated species, Arabica coffee (*Coffea arabica*) holds the top position in global preferences due to its superior sensory profile, balanced acidity, and rich floral and fruity aroma absent in other varieties (Siregar et al., 2020). Beyond its organoleptic attributes, coffee contains antioxidant compounds capable of scavenging free radicals, stimulating cognitive function, and exhibiting protective anti-cancer properties. Nevertheless, coffee consumption is often constrained by high caffeine content. In Arabica coffee, caffeine accounts for 1.4% to 2.4% of total dry weight (Swiranata et al., 2020). For sensitive individuals, excessive intake can trigger physiological side effects, such as gastric mucosal irritation, nausea, tachycardia, anxiety, and insomnia (Rosalinda et al., 2021). Therefore, developing sustainable decaffeination methods is crucial to reduce caffeine levels without compromising flavor and aroma quality.

Conventional chemical solvent-based decaffeination is often criticized for leaving toxic residues and deteriorating the organoleptic quality of coffee beans. As an alternative, fermentation utilizing microbial starters continues to be explored as a natural bio decaffeination medium while enhancing flavor profiles (Saripah et al., 2021). Theoretically, extending fermentation periods can optimize caffeine reduction provided that the viability of degrading microorganisms is maintained (Hamad et al., 2023). However, controlling fermentation is often hindered because microbial metabolic activity and community succession are vulnerable to fluctuations in environmental parameters (Ferreira et al., 2023; Todhanakasem et al., 2024). For example, cabbage-waste microorganisms producing pectinolytic enzymes were reported to reduce caffeine by more than 96% (Hariyadi et al., 2024). Meanwhile, the 28.9% reduction observed with tape yeast was lower, presumably due to the absence of specialized pectinolytic enzymes and disparities in the physical conditions of the fermentation medium. The microbial biotransformation of caffeine occurs through N-demethylation and C-8 oxidation pathways (Ran et al., 2025). The kinetic efficiency of enzymatic reactions in both pathways is highly dependent on environmental stability, including pH, operational temperature, moisture content, and dissolved oxygen availability.

In response to these instability challenges, the introduction of innovative, environmentally friendly, non-thermal, and precisely controllable technologies is urgently needed (Radil et al., 2024). Exposure to Extremely Low Frequency (ELF) magnetic fields emerges as an advanced biophysical method capable of stimulating microbial intracellular bioprocesses during fermentation. This non-ionizing radiation influences the polarization and permeability of microbial cell membranes, accelerates nutrient ion transport, and enhances the rate of caffeine reduction without degrading the volatile precursors of coffee. Empirically, ELF radiation has been proven to significantly boost biomass accumulation and metabolic productivity in the yeast *Saccharomyces cerevisiae* compared to controls (Sincak et al., 2024). In coffee fermentation applications, ELF intervention accelerated metabolic kinetics as indicated by a decreasing pH curve (Purbawati et al., 2021), significantly reduced caffeine in coffee pulp at intensities below 500 μ T (Komaria et al., 2023), and stimulated the proliferation of *Lactobacillus* bacteria at an intensity of 300 μ T (Sudarti et al., 2020).

Although promising, biological responses induced by ELF magnetic field exposure vary depending on the material matrix, field intensity, and exposure duration. The specific characteristics of Arabica beans demand an investigation of dedicated physical parameters. Therefore, comprehensive research on caffeine reduction in Arabica coffee beans through ELF magnetic field-assisted fermentation is imperative. This study provides scientific evidence regarding the bio stimulation effectiveness of ELF waves, delivering a

modern, economically efficient, environmentally safe breakthrough in coffee processing capable of producing high-value, low-caffeine coffee products with superior quality and high commercial viability.

Materials and method

Materials and equipment

Six kilograms of premium-grade dry Arabica coffee beans from a local plantation on Jl. Kawah Ijen, Bondowoso, East Java, and tape yeast as the microbial starter were used. The beans were divided into six groups: negative control (no treatment or yeast), positive control (yeast fermentation without ELF exposure), and four experimental groups exposed to 300 or 500 μ T for 30 or 60 min. Fermentation was conducted in food-grade plastic containers fitted with airlocks to allow gas release. The ELF field was generated using a custom-built Current Transformer (CT) unit operating at 50 Hz. During exposure, the containers were placed on a non-magnetic platform at the center of the ELF cage to ensure uniform magnetic-field exposure.

Research methods

A 3 $\times$ 2 factorial experimental design was used. The factors were Extremely Low Frequency (ELF) magnetic field intensity (control, 300 μ T, and 500 μ T) and exposure duration (30 and 60 minutes). The experimental design was outlined in Figure 1. The treatment groups were: C1, negative control with no applied treatment; C2, positive control undergoing fermentation without ELF exposure; E1.1, 300 μ T for 30 minutes; E1.2, 300 μ T for 60 minutes; E2.1, 500 μ T for 30 minutes; and E2.2, 500 μ T for 60 minutes. ELF exposure was applied at the 5th, 10th, 15th, and 20th hours of fermentation. Each treatment group was prepared in one independent fermentation container, representing one biological replicate per group ($n = 1$). To ensure analytical precision, 15 technical replicates (repeated instrumental measurements) were collected from each container at each fermentation pH observation interval (5th, 10th, 15th, and 20th hours) and for the final post-drying bean characterizations (bean pH, density, and caffeine content). These 15 technical measurements per group were used as the individual data points for statistical analysis. Data were analyzed using IBM SPSS 27. Because the unexposed control groups did not fit a fully crossed factorial grid, One-Way ANOVA was used. Normality and homogeneity were tested ($p > 0.05$). Normally distributed data were analyzed by One-Way ANOVA followed by Least Significant Difference (LSD) post-hoc tests ($p < 0.05$). Non-parametric data were analyzed using the Kruskal-Wallis test, followed by Mann-Whitney U post-hoc pairwise comparisons ($p < 0.05$).

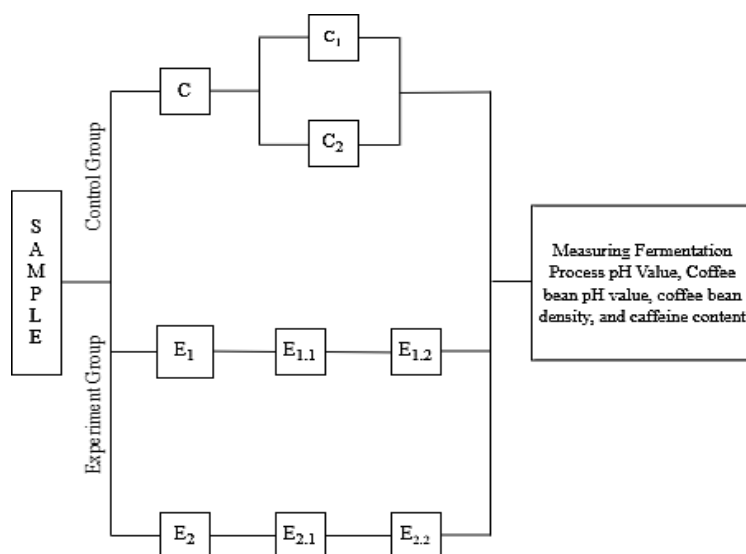


Figure 1. Research design

Research procedures

Arabica coffee bean samples were fermented in food-grade containers using 10 g of tape yeast and 2 L of distilled water. The tape yeast contained a microbial consortium primarily consisting of *Saccharomyces cerevisiae*, *Candida* sp., *Rhizopus* sp., and *Lactobacillus* sp. ELF exposure was applied using magnetic field intensities of 300 μ T and 500 μ T with exposure durations of 30 and 60 minutes. During fermentation, the pH of the fermentation medium was measured. After fermentation, the beans were dried in an oven at 50°C for 24 hours until reaching a moisture content of approximately 10–12%, then ground into powder.

Research parameters

(1) pH measurement

pH was measured during fermentation and on pulverized coffee beans using a digital pH meter, following standard analytical protocols for food and beverage fermentation (AOAC, 2019; Shen et al., 2025).

(2) Density measurement

Dried coffee beans were weighed (m , g) and submerged in 10 ml of water (V_0). The final displaced volume (V_1 , ml) was recorded. Bean density was calculated as:

$$\rho = \frac{m}{V_1 - V_0} \quad (1)$$

Where ρ is specific density (g/cm^3), m is dried bean mass (g), V_0 is initial water volume (10 ml), and V_1 is the final displaced volume (ml). This volume displacement method is consistent with physical characterization approaches used for agricultural seeds and coffee beans (Martinez et al., 2022; Ferreira et al., 2023).

(3) Caffeine content

Caffeine content was analyzed at the Functional Food and Nutraceutical Laboratory, Faculty of Agricultural Technology, Universitas Jember, using UV-Vis spectrophotometry. The extraction and spectrophotometric quantification were adapted from standardized methods for caffeine degradation analysis (Ran et al., 2025; Hamad et al., 2023). Absorbance was measured at 275 nm. Caffeine mass was determined using the standard curve:

$$y = 53.165x - 0.0244 \quad (2)$$

where y is sample absorbance and x is caffeine mass (mg). Caffeine concentration was then calculated as:

$$K = \frac{m}{V} \quad (3)$$

where K is caffeine concentration (mg/ml), m is caffeine mass obtained from the standard curve (mg), and V is solution volume (ml). Final caffeine content was calculated as:

$$K_k = \frac{K \times V}{m_s} \quad (4)$$

where K_k is final caffeine content in the beans (mg/g), K is caffeine concentration from Equation 3 (mg/ml), V is total solution volume (ml), and m_s is the initial mass of the analyzed coffee sample (g). Caffeine content was converted to percentage using the equivalence 1% caffeine = 10 mg/g.

Results and discussion

Quality of the ELF magnetic field-assisted fermentation process

All treatments exhibited a time-dependent pH decrease during fermentation (Figure 2). At 20 hours, the positive control had the lowest mean pH (4.14), while the ELF-exposed groups maintained slightly higher pH values, with the highest value observed in the 300 μ T/30-min group (4.43). The negative control was excluded from the fermentation-pH analysis because it did not undergo wet fermentation or ELF exposure and remained at a stable baseline pH.

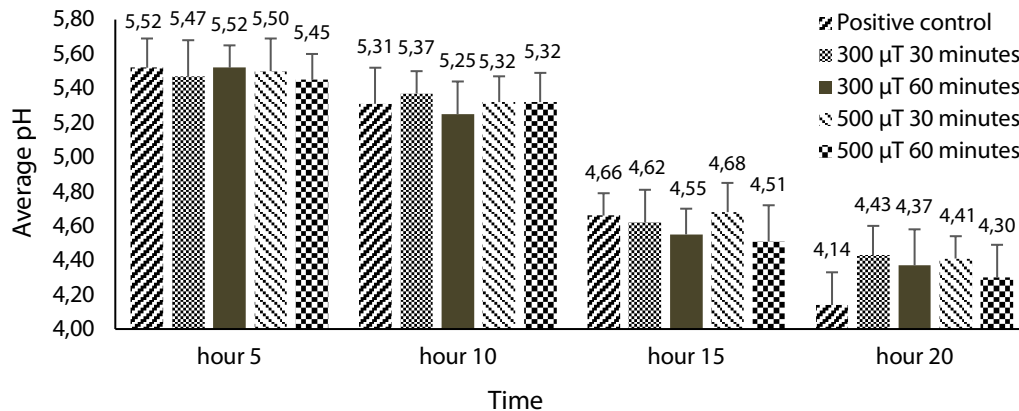


Figure 2. Average pH of the fermentation process

Normality and homogeneity tests conducted on the fermentation pH data at each 5-hour observation interval yielded p-values greater than 0.05, indicating that the data were normally distributed and had homogeneous variance. Therefore, One-Way ANOVA was applied (Table 1). One-Way ANOVA showed no significant differences among groups at 5 hours ($p = 0.749$) or 10 hours ($p = 0.463$). Significant differences emerged at 15 hours ($p = 0.043$) and 20 hours ($p < 0.001$), prompting LSD post-hoc tests.

Table 1. Results of the one-way ANOVA test

Observation Time	Variation	One way ANOVA			F	Sig.
		Sum of Squares	df	Mean Square		
Hour 5	Between Groups	0.058	4	0.015	0.482	0.749
	Within Groups	2.112	70	0.030		
	Total	2.170	74			
Hour 10	Between Groups	0.110	4	0.027	0.910	0.463
	Within Groups	2.112	70	0.030		
	Total	2.222	74			
Hour 15	Between Groups	0.314	4	0.078	2.600	0.043
	Within Groups	2.112	70	0.030		
	Total	2.426	74			
Hour 20	Between Groups	0.825	4	0.206	6.835	< 0.001
	Within Groups	2.112	70	0.030		
	Total	2.937	74			

At 20 hours, significant pH differences were observed between the positive control and all ELF-exposed groups. The positive control had a substantially lower pH than the ELF-treated groups. This pH decline is consistent with normal coffee fermentation, in which microorganisms catabolize carbohydrates and produce organic acids, including lactic and acetic acids (Ferreira et al., 2023; Pereira et al., 2022; Shen et al., 2024). The accumulation of organic acids increases hydrogen ion concentration and lowers pH (Sudarti et al., 2020).

ELF exposure appears to moderate this acidification rather than prevent fermentation. This effect may be related to ELF-induced modulation of membrane ion transport and microbial metabolism (Azizah et al., 2022; Radil et al., 2024). However, direct regulation of transmembrane proton pumps or

intracellular buffering was not measured in this study and should therefore be interpreted as a possible mechanism rather than a demonstrated effect.

Quality of Arabica coffee beans following ELF magnetic field-assisted fermentation

(1) Arabica coffee bean pH

ELF-exposed beans exhibited higher mean pH values than the positive control, although the negative control remained highest (7.70). Mean bean pH values were: negative control, 7.70; positive control, 6.41; 300 μ T/30 min, 6.69; 300 μ T/60 min, 6.86; 500 μ T/30 min, 6.53; and 500 μ T/60 min, 6.61 (Figure 3). Lower intensities (300 μ T) generally produced higher bean pH than the 500 μ T treatments.

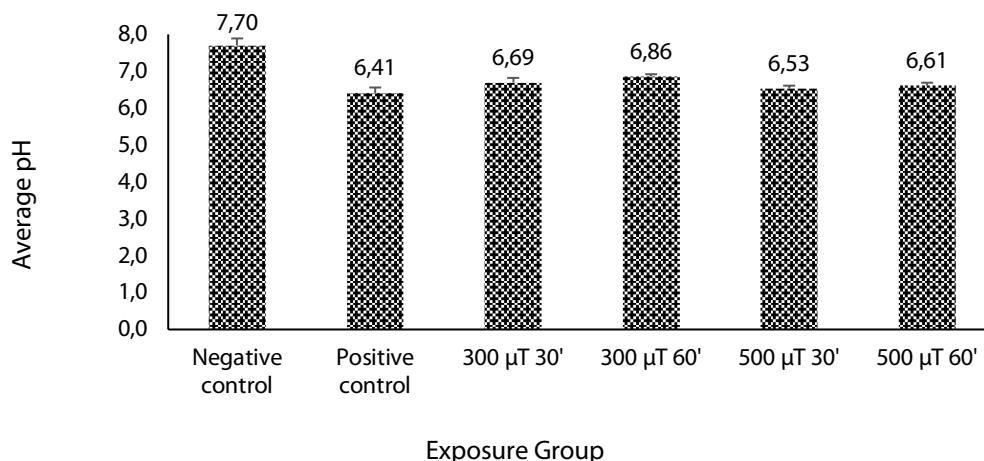


Figure 3. Average pH of arabica coffee beans

Table 2. Kruskal-Wallis test results

Test Statistics ^{a,b}	
Coffee Bean pH	
Kruskal-Wallis H	71.069
df	5
Asymp. Sig.	< 0.001

Because normality assumptions were not met for some groups ($p < 0.05$), the Kruskal-Wallis test was used. The Kruskal-Wallis test showed highly significant differences among groups ($H = 71.069$; $df = 5$; Asymp. Sig. $p < 0.001$). Mean-rank analysis ordered bean pH from highest in the negative control to lowest in the positive control. Mann-Whitney U post-hoc comparisons showed significant differences (Exact Sig. $p \leq 0.023$) for the negative control, positive control, 300 μ T/60-min, and 500 μ T/30-min groups when compared with the other treatment cohorts. However, no significant difference was observed between the 300 μ T/30-min and 500 μ T/60-min groups (Exact Sig. $p = 0.116$).

(2) Arabica coffee bean density

Mean bean density ranged from 0.76 g/cm³ in the negative control to 1.21 g/cm³ in the 500 μ T/60-min group (Figure 4). Mean density values were: negative control, 0.76; positive control, 0.96; 300 μ T/30 min, 1.08; 300 μ T/60 min, 0.96; 500 μ T/30 min, 1.12; and 500 μ T/60 min, 1.21 g/cm³. The highest densities were observed at 500 μ T, particularly with 60-minute exposure, although the 300 μ T/60-min group did not exceed the positive control. Because the density data were not normally distributed ($p < 0.05$), the Kruskal-Wallis test was used. The Kruskal-Wallis test result presented in Table 3 confirmed significant differences among groups ($H = 44.354$; $df = 5$; Asymp. Sig. $p < 0.001$). Mann-Whitney U post-hoc tests showed that the negative control differed significantly from all other groups (Exact Sig. $p < 0.005$). The 500 μ T/60-min group differed significantly from all groups except the 500 μ T/30-min group (Exact Sig. $p \leq 0.05$).

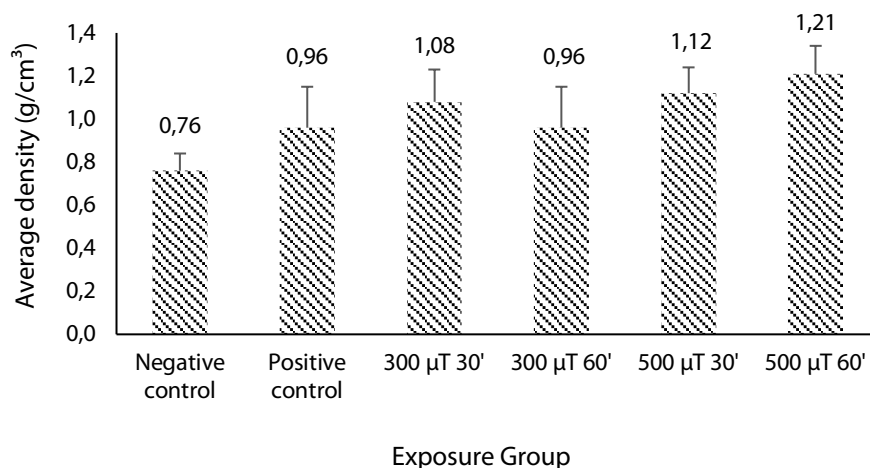


Figure 4. Average density of arabica coffee beans

Table 3. Kruskal-Wallis test results

Test Statistics ^{a,b}	
	Coffee Bean Density
Kruskal-Wallis H	44.354
df	5
Asymp. Sig.	< 0.001

The observed density changes may reflect fermentation- and ELF-associated changes in water uptake, ion movement, membrane permeability, and structural modification of the bean matrix (Masita et al., 2023). They may also be related to microbial degradation of mucilage and moisture redistribution during fermentation and drying (Martinez et al., 2022; Ferreira et al., 2023). Because density depends on both mass and displaced volume, the present data indicate net changes in bean mass/volume but do not directly identify which component changed most. From a quality perspective, higher bean density may be desirable because it can correlate with better structural integrity, more uniform roasting, and improved extraction of flavor compounds.

(3) Arabica coffee bean caffeine content

A standard caffeine solution of 1 mg/ml functioned as the reference calibrator, as illustrated in the Figure 5. Caffeine was quantified using a caffeine standard curve (Figure 5), and the results are summarized in Table 4. The negative control had the highest caffeine content ($0.0329 \pm 0.0003\%$). The positive control showed a lower value ($0.0237 \pm 0.0001\%$). All ELF-exposed groups had lower caffeine content than the negative control. The lowest caffeine content was observed in the 300 µT/30-min group ($0.0234 \pm 0.0002\%$), followed by 300 µT/60 min ($0.0242 \pm 0.0008\%$), 500 µT/30 min ($0.0258 \pm 0.0001\%$), and 500 µT/60 min ($0.0262 \pm 0.0001\%$).

Relative to the negative control, the 300 µT/30-min treatment corresponded to a 28.9% lower caffeine content. Relative to the positive control, however, the same treatment was only slightly lower (0.0234% versus 0.0237%), while the other ELF treatments were equal to or higher than the positive control. This pattern suggests that fermentation itself was the major factor associated with caffeine reduction, while ELF exposure may have modulated the process in an intensity- and duration-dependent manner. The 300 µT/30-min condition produced the lowest observed caffeine content, but statistical comparison with the positive control should be reported to support a specific ELF effect.

The lower caffeine content observed at 300 µT/30 min may result from interactions between microbial metabolism and mass transfer. Coffee fermentation involves the dynamic succession of bacteria, yeasts, and filamentous fungi, whose metabolic activities modify the mucilage, bean matrix, and soluble

metabolite profiles (Ferreira et al., 2023; Shen et al., 2025; Todhanakasem et al., 2024). Organic acid production and enzymatic weakening of the bean matrix may facilitate movement of water-soluble compounds, including caffeine, between the bean and fermentation medium (Ferreira et al., 2023; Shen et al., 2025). ELF fields may additionally affect membrane permeability and ion transport (Azizah et al., 2022; Radil et al., 2024), potentially enhancing this mass-transfer process. Microbial caffeine degradation pathways, including N-demethylation, have also been described (Ran et al., 2025). However, direct upregulation of microbial N-demethylase enzymes by ELF exposure was not measured in this study and should therefore be considered a hypothesis for future investigation.

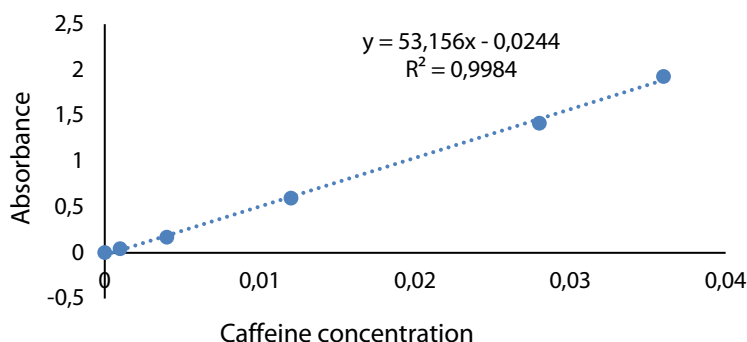


Figure 5. Caffeine standard curve

Table 4. Caffeine content test results

Group	Test Result (%) $\pm$ SD
Positive Control	0.0237 $\pm$ 0.0001
Negative Control	0.0329 $\pm$ 0.0003
300 μ T / 30 min Sample	0.0234 $\pm$ 0.0002
300 μ T / 60 min Sample	0.0242 $\pm$ 0.0008
500 μ T / 30 min Sample	0.0258 $\pm$ 0.0001
500 μ T / 60 min Sample	0.0262 $\pm$ 0.0001

The higher caffeine values observed in the 500 μ T groups, particularly after 60-minute exposure, suggest that excessive ELF exposure may reduce the efficiency of caffeine reduction. This may reflect altered microbial redox balance or ROS homeostasis under electromagnetic stress. Chen et al. (2023) showed that ELF-EMF can increase ROS levels in microbial cells, while Guzmán-Armenteros et al. (2024) described intensity-dependent EMF effects on microbial growth and fermentation parameters. Therefore, the present results are consistent with a non-linear response in which moderate ELF exposure may support decaffeination-related fermentation, while excessive exposure may be less favorable.

Conclusion

ELF magnetic field exposure moderated the fermentation pH decline and was associated with changes in bean pH and density. The highest fermentation pH at 20 hours among ELF-treated groups was observed at 300 μ T/30 min. ELF-exposed beans generally showed higher pH and density than the positive control, although the negative control remained highest for bean pH and lowest for density. The lowest caffeine content was observed in the 300 μ T/30-min group, corresponding to a 28.9% reduction relative to the negative control. However, this value was only slightly lower than the positive control, indicating that fermentation itself contributed substantially to caffeine reduction and that the additional ELF effect should be confirmed statistically.

Overall, the results suggest that ELF-assisted fermentation may influence physical and chemical indicators of coffee fermentation, including pH, density, and caffeine content. These effects are likely related to interactions among microbial activity, organic acid production, structural modification of the

bean matrix, and mass transfer of soluble compounds. Future studies should include biological replication, direct statistical comparisons between ELF-treated and positive-control groups, and standardized microbial starters to improve reproducibility and support commercial application.

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