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Final Moisture Content and Energy Use in Microwave Drying of Green Robusta Coffee Beans from Dampit at Different Temperatures

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A B S T R A C T

This study evaluated final moisture content and energy use in microwave drying of green Robusta coffee beans from Dampit, East Java, Indonesia. Batches of 45 g were dried at 34–46 °C for 30 min, with three independent runs per temperature. Measurements supported functional mapping using the Function Analysis System Technique. From 34 to 46 °C, final moisture content decreased from 10.55% to 8.80% on a dry basis. Electricity consumption increased from 0.156 to 0.219 kWh per run, whereas specific energy consumption decreased from 312.5 to 181.0 kWh/kg water removed. Higher temperatures therefore required more electricity per run but less per unit of estimated water removal. Temperature recommendations require mass-balance verification and product-quality assessment

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INTRODUCTION

Drying reduces the moisture content of coffee beans before handling and storage. Drying temperature and duration require careful control because they affect moisture transfer and may influence bean quality. Previous studies have linked drying conditions to physiological responses and sensory quality in coffee (Isquierdo et al., 2013 ;Borém et al., 2013 ;Sandeep et al., 2021 Fernando et al., 2025).

Product quality is another consideration when selecting drying conditions. Drying methods and postharvest handling have been associated with differences in bioactive compounds, color, aroma, and beverage quality (Dong et al., 2017 ;Kulapichitr et al., 2019 ;Kulapichitr et al., 2022 ; Cortés-Macías et al., 2022). These relationships support evaluating drying performance beyond moisture reduction alone.

Final moisture content describes the beans' condition after drying. Assessing their suitability for storage also requires information on water activity, storage conditions, and product quality. Studies of coffee storage, water sorption, and drying indicate that bean responses also depend on the material's initial condition and the equipment used (Estrada-Bahena et al., 2022 ;Borém et al., 2013 ;Alves Rocha et al., 2022 ;Coradi et al., 2021) .

Microwave heating transfers energy to the material. The resulting response depends on power, sample mass and arrangement, pressure, and temperature control. Recent studies on microwave processing of coffee have further shown that operating power and exposure time influence process performance, energy efficiency, and the retention of quality-related compounds (Yuniati, Jimmy, et al., 2025) ; (Yuniati, Ningtyas, et al., 2025) . Previous studies have developed several approaches to power and temperature control during microwave drying (Cheng et al., 2006 ;Li et al., 2010 ;Cao et al., 2017 ;Monteiro et al., 2020). Consider these differences in equipment configuration when comparing systems. The present study used microwave drying at atmospheric pressure with temperature control.

One aspect of equipment performance is its ability to maintain the selected temperature. However, a mean temperature near the setpoint does not ensure uniform heating throughout the material. Studies of microwave drying have reported variations in temperature and moisture within samples. They have also examined how magnetron arrangement and material movement affect heating uniformity (Z. Y. Li et al., 2011 ; Wang et al., 2016; Huang et al., 2016 ;Jiang et al., 2014) .

Energy use is also relevant when selecting drying conditions. Total energy represents the electricity consumed in one experimental run. Specific energy consumption (SEC) is the energy consumed per kilogram of water removed, with water removal estimated from moisture measurements. Both indicators should be considered because they describe different aspects of the process (Sharma & Prasad, 2006 ;Soysal et al., 2006 ;Zhang et al., 2023 ; Lin et al., 2023).

Comparisons at a fixed drying time can reveal differences in final product conditions and energy requirements. Kinetic analysis requires moisture measurements throughout drying, while estimating effective moisture diffusivity also requires a mass transfer model (Dak & Pareek, 2014) ; (G. P.

Sharma & Prasad, 2004). This article compares final outcomes across treatments using initial moisture content and measurements after 30 min.

This study aimed to compare final moisture content and energy use during microwave drying of Robusta coffee beans for 30 min at 34, 38, 42, and 46 °C. Measurements included product temperature, moisture content, batch mass, electricity consumption, and the duration of each recorded activity. These data were used to calculate estimated water removal, SEC, and the batch processing rate, defined as the initial batch mass divided by the recorded cycle time. The Function Analysis System Technique (FAST) was used to explain the relationships between drying functions and the measured indicators. The findings may inform the selection of operating conditions according to moisture targets and energy requirements.

LITERATURE REVIEW

Microwave processing of coffee requires consideration of both process performance and product quality. Dong et al. (2018) examined microwave vacuum drying of green coffee beans and found that microwave power affected bean porosity, colour, total phenolic content, and antioxidant activity. More recently, Yuniati et al. (2026) evaluated low-temperature microwave-assisted drying of Arabica coffee beans and reported temperature-dependent differences in drying kinetics, colour response, and energy performance. These findings reinforce the need to evaluate moisture removal alongside energy use and product quality, rather than moisture reduction alone (Kaufman & Woodhead, 2006) .

Energy assessment also requires indicators that distinguish electricity consumption from the amount of drying achieved. Specific energy consumption expresses energy use per unit of water removed and has been investigated in microwave drying applications (G. Sharma & Prasad, 2006). Its interpretation depends on both the measured energy input and the estimated water removal. A treatment may consume more electricity per run while requiring less energy per kilogram of water removed. Comparisons should therefore report both indicators and account for batch mass, initial moisture content, drying duration, and the measurement boundary. This distinction is particularly relevant when small quantities of water are removed.

The present study applies these considerations to green Robusta coffee beans from Dampit, East Java, Indonesia by comparing four temperatures at a fixed drying duration. Final moisture content, electricity consumption, specific energy consumption, and recorded cycle time provide complementary descriptions of the experimental outcomes. The Function Analysis System Technique connects these indicators to drying and supporting functions, making their roles in process evaluation explicit. The study thus provides a descriptive comparison under defined laboratory conditions, while product quality assessment and mass balance verification remain necessary for broader operating recommendations

METHODOLOGY

This study used a laboratory experimental design to evaluate the drying performance of unroasted Robusta coffee beans (Coffea canephora) at different temperature setpoints. Coffee beans were obtained from Dampit, East Java, Indonesia. The treatments consisted of drying temperatures of 34, 38, 42, and 46 °C for 30 min, with three independent runs for each treatment using a fresh batch of approximately 45 g, resulting in 12 experimental units. Drying was conducted using an Electrolux EMC27D22BM microwave unit with a nominal power of 900 W equipped with a TCG-B6131 temperature controller. Product temperature was recorded using a 174T data logger. Ambient temperature was approximately 25 °C, with relative humidity ranging from 60.5% to 63.0%. Electricity consumption was measured using an external electricity meter.

Table 1. Experimental conditions and indicator definitions

Item	**Definition used in this study**
Material	Green Robusta coffee beans from Dampit; initial batch mass of approximately 45 g
Treatment	Temperature setpoints of 34, 38, 42, or 46 °C; a fixed heating duration of 30 min; three independent runs per temperature
Drying outcomes	Final moisture content (% d.b.) and estimated water removal calculated from moisture content (g)
Laboratory measurements	Minimum required sample mass of 5 g; two technical readings recorded per experimental run
Energy measurement	Difference between external meter readings for one treatment run (kWh)
Cycle time	Preparation + heating + unloading + cooling; unrecorded activities excluded (min)
Calculated indicators	SEC (kWh kg^{-1} water removed), cycle time (min), and batch processing rate (kg h^{-1})

Initial and final batch masses were recorded in grams, while moisture content was determined on a dry basis (% d.b.) using a minimum sample mass of 5 g. Two technical moisture readings were obtained for each experimental run and averaged to obtain the run-level value. Dry solids mass and estimated water removal were calculated from the initial and final moisture contents, assuming constant dry solids mass during drying. Measured mass loss was calculated from the difference between initial and final batch masses. Electricity consumption was determined from the difference between the initial and final readings of the external meter. Specific energy consumption (SEC) was calculated as electricity consumption (kWh) per kilogram of estimated water removed. Cycle time consisted of preparation, heating, unloading, and cooling, while batch processing rate was calculated from the initial batch mass and cycle time. Activities with unavailable duration data, including moisture testing, record keeping, cleaning, and idle time, were excluded.

Functional Analysis System Technique (FAST) was used to describe the functional relationships within the drying process. The main function was defined as preparing coffee beans for handling, while moisture reduction was

identified as the basic process function (Kaufman, 1997) . The FAST diagram described the relationship between heat application, water evaporation, temperature control, and exposure time. The analysis was used to clarify the drying process and was not used to assign treatment scores or rankings.

Data were analysed descriptively using Microsoft Excel. Mean and sample standard deviation were calculated from the three independent runs for each temperature. Moisture content, estimated water removal, electricity consumption, SEC, cycle time, and batch processing rate were reported in their original units. The two technical moisture readings were averaged within each run before analysis, and their differences were examined to assess measurement consistency. The treatment outcomes after 30 min were compared descriptively without inferential significance testing or construction of a composite score.

RESEARCH RESULT

Final Moisture Content and Measurement Agreement

Mean product temperatures at setpoints of 34, 38, 42, and 46 °C were 34.23, 38.23, 42.13, and 46.13 °C, respectively (Table 2). The difference between each mean temperature and its setpoint did not exceed 0.23 °C. Initial moisture content averaged 11.80% on a dry basis across treatments. After 30 min, final moisture content decreased progressively from 10.55 ± 0.05% at 34 °C to 10.00 ± 0.10%, 9.50 ± 0.10%, and 8.80 ± 0.10% at 38, 42, and 46 °C, respectively.

Laboratory moisture measurements followed the same pattern, with treatment means of 10.542, 9.995, 9.497, and 8.800% on a dry basis. The mean absolute difference between paired technical readings ranged from 0.057 to 0.087 percentage points across treatments; the largest individual difference was 0.10 percentage points. The maximum difference between the laboratory mean for a run and its corresponding process record was 0.025 percentage points.

Estimated water removal increased from 0.504 ± 0.052 g at 34 °C to 1.209 ± 0.039 g at 46 °C. Measured mass loss increased from 0.827 ± 0.006 to 1.190 ± 0.017 g. The differences between measured mass loss and estimated water removal were 0.323, 0.247, 0.156, and −0.019 g at 34, 38, 42, and 46 °C, respectively.

Table 2. Product temperature, moisture content, and mass changes after 30 min of drying.

Table 2. Product temperature, moisture content, and mass changes after 30 min of drying.

Setpoint (°C)	Product temperature (°C)	Initial moisture (% d.b.)	Final moisture (% d.b.)	Laboratory moisture (% d.b.)	Estimated water removal (g)	Measured mass loss (g)
34	34.23 ± 0.15	11.80 ± 0.10	10.55 ± 0.05	10.542 ± 0.038	0.504 ± 0.052	0.827 ± 0.006
38	38.23 ± 0.15	11.80 ± 0.10	10.00 ± 0.10	9.995 ± 0.093	0.726 ± 0.039	0.973 ± 0.012
42	42.13 ± 0.15	11.80 ± 0.10	9.50 ± 0.10	9.497 ± 0.095	0.927 ± 0.081	1.083 ± 0.025
46	46.13 ± 0.15	11.80 ± 0.10	8.80 ± 0.10	8.800 ± 0.100	1.209 ± 0.039	1.190 ± 0.017

Note. Values are means ± sample standard deviations from three independent runs per temperature. For laboratory moisture content, we averaged the two technical readings within each run before calculating the treatment mean and standard deviation. The minimum sample mass required for laboratory testing was 5 g. Estimated water removal was calculated from moisture content on a dry basis, whereas measured mass loss was obtained from the difference between the initial and final batch masses.

Energy Use and Processing Time

Electricity consumption increased with temperature, from 0.156 ± 0.002 kWh per run at 34 °C to 0.219 ± 0.002 kWh per run at 46 °C (Table 3). Over the same temperature range, specific energy consumption decreased from 312.5 ± 29.3 to 181.0 ± 4.2 kWh/kg water removed. Based on the displayed treatment means, electricity consumption increased by approximately 40%, while estimated water removal increased by approximately 140%. Figure 1 presents these changes alongside final moisture content.

Recorded cycle time ranged from 45.43 to 45.70 min, and batch processing rate ranged from 0.0592 to 0.0595 kg/h. The fixed 30 min heating period accounted for approximately 65.6–66.0% of cycle time. Cycle time and batch processing rate differed little across the four temperatures.

Table 3. Energy use and processing time at each drying temperature

Setpoint (°C)	Energy (kWh run⁻¹)	Mean power (W)	SEC (kWh kg⁻¹ water removed)	Cycle time (min)	Batch processing rate (kg h⁻¹)
34	0.156 ± 0.002	312.7 ± 4.5	312.5 ± 29.3	45.43 ± 0.06	0.05948 ± 0.00005
38	0.178 ± 0.002	357.0 ± 2.6	246.2 ± 11.2	45.67 ± 0.25	0.05921 ± 0.00032
42	0.197 ± 0.002	392.3 ± 4.7	213.2 ± 19.1	45.70 ± 0.20	0.05918 ± 0.00018
46	0.219 ± 0.002	437.7 ± 3.5	181.0 ± 4.2	45.70 ± 0.00	0.05916 ± 0.00005

Note. Values are means ± sample standard deviations from three independent runs per temperature. SEC was calculated using estimated water removal. The batch processing rate was calculated by dividing the initial batch mass by the combined duration of preparation, heating, unloading, and cooling.

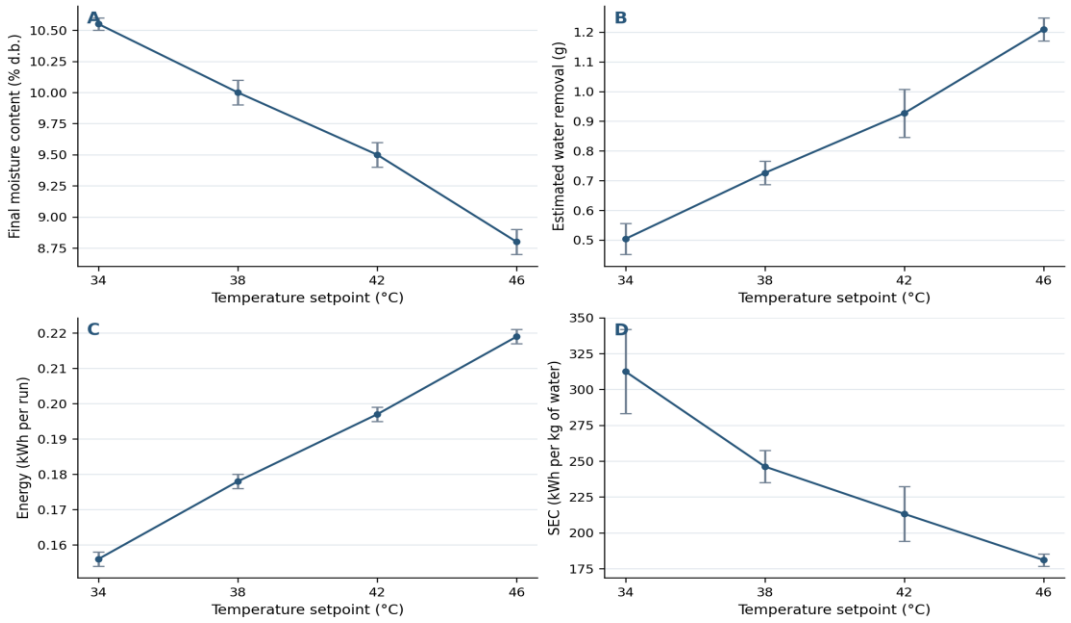


Figure 1. Final moisture content (A), estimated water removal (B), electricity consumption (C), and specific energy consumption (D) at each drying temperature. Points represent means, and error bars represent sample standard deviations from three independent runs. Lines connect treatment means and do not represent drying kinetics.

Functional Relationships

Figure 2 presents the FAST mapping of the drying process. Reducing moisture content is the basic function; water evaporation and heat application represent the HOW chain, whereas preparing beans for handling represents the higher-order WHY function. Temperature control and exposure time support heat application. Measurements of moisture content, mass, electricity consumption, and activity duration support experimental evaluation rather than the physical drying sequence. The diagram therefore links each indicator to its

role without assigning treatment scores or combining indicators into a single performance measure.

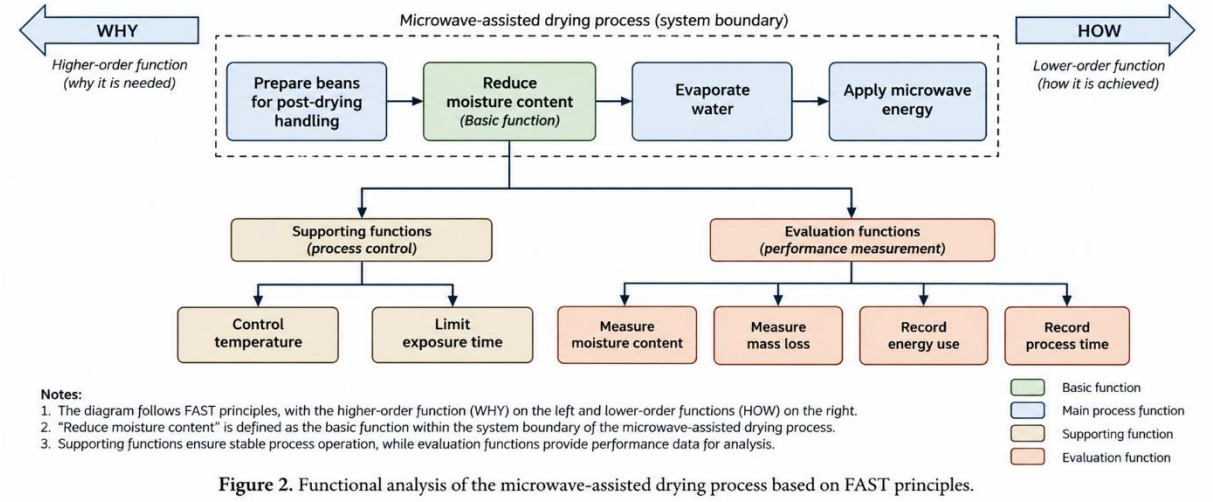


Figure 2. FAST functional relationships for the microwave drying process. The horizontal chain shows why–how logic from the higher-order function to the basic and secondary functions. Process-control and experimental-evaluation functions are shown below the chain as supporting functions; arrows indicate functional logic rather than chronological sequence.

DISCUSSION

Temperature and Final Moisture Content

At a fixed drying duration, higher temperatures were associated with lower final moisture content. This pattern is consistent with previous coffee drying studies that examined the influence of drying conditions on moisture removal (Isquierdo et al., 2013) ;(Borém et al., 2018). However, the magnitude of moisture reduction depends on the initial condition of the beans and the equipment used. The present results therefore support comparisons among the four treatments within this experimental system.

The small differences between mean product temperatures and their setpoints describe agreement at the recorded measurement location. They do not establish uniform temperatures throughout the beans or microwave chamber. Likewise, measurements taken only before and after 30 min describe final outcomes but cannot identify drying phases, fit drying kinetics, or establish the mechanism controlling moisture transfer.

Electricity Consumption and Specific Energy Consumption

The opposing changes in electricity consumption and specific energy consumption arise from their different calculation bases. Electricity consumption measures the energy used in one run, whereas specific energy consumption relates that input to water removal (Sharma & Prasad, 2006) ;(Soysal et al., 2006) . At 46 °C, estimated water removal increased proportionally more than electricity consumption. Consequently, energy use per kilogram of water removed decreased even though each run consumed more electricity.

This distinction affects temperature selection. The 46 °C treatment had the lowest specific energy consumption under the tested conditions, but it did not minimise electricity consumption per run. The comparison also used a fixed drying duration, so the treatments produced different final moisture contents. An energy comparison at a common final moisture target would require additional experiments.

Interpret the absolute specific energy consumption values in relation to the small amount of water removed, approximately 0.5–1.2 g per run. Dividing the measured electricity consumption by this small quantity produces high values per kilogram of water removed. These results characterise the tested batch size and equipment; extrapolation to larger batches requires measurements of energy consumption and water removal at the intended scale.

Measurement Consistency and Interpretation

The close agreement between laboratory moisture values and process records supports consistency between the reported measurements. Nevertheless, the procedure used to obtain the paired technical readings must be specified before assessing repeatability. Technical readings also do not increase the number of independent experimental units, which remains three per temperature.

The discrepancy between measured mass loss and estimated water removal is more consequential for energy interpretation. At 34 °C, measured mass loss exceeded estimated water removal by 0.323 g, whereas the difference at 46 °C was −0.019 g. The available records do not establish the cause of this discrepancy. Weighing procedures, moisture sampling, calculation bases, and the assumption of constant dry solids mass require examination. Because estimated water removal is the denominator in specific energy consumption, uncertainty in this estimate directly affects the resulting values and comparisons.

Functional Interpretation and Operating Implications

The FAST diagram makes the role of each performance indicator explicit. Final moisture content provides evidence for the basic function of reducing moisture. Electricity consumption and recorded time describe inputs associated with heat application and process control, while SEC relates electricity use to estimated water removal. Cycle time and batch processing rate describe the recorded sequence of laboratory activities. Their limited variation reflects the fixed heating duration, similar batch masses, and comparable handling times. The reported processing rate applies to this recorded cycle, which excludes unmeasured activities such as cleaning and idle time.

Temperature selection should start with a defined moisture target, then consider energy requirements among treatments that achieve it. Product quality remains an additional criterion. Dong et al. (2018) reported changes in colour, phenolic content, and antioxidant activity during microwave vacuum drying of green coffee beans. Yuniati et al. (2026) likewise reported a temperature-related trade-off between drying efficiency and colour preservation in microwave-dried Arabica coffee beans. These findings provide context for future quality

measurements but do not establish quality changes during the drying treatments examined here.

The present evidence therefore does not establish an optimum temperature. Further work should verify the mass balance, compare energy use at a common final moisture target, and measure product quality and water activity. Larger batches and temperature measurements at multiple locations would also help determine whether the observed relationships persist beyond the current laboratory conditions.

CONCLUSIONS AND RECOMMENDATIONS

When approximately 45 g batches of Robusta coffee beans were dried for 30 min, final moisture content decreased from 10.55% d.b. at 34 °C to 8.80% d.b. at 46 °C. Electricity consumption increased from 0.156 to 0.219 kWh per run, whereas SEC decreased from 312.5 to 181.0 kWh per kg of water removed. Cycle time remained similar at 45.43–45.70 min. Drying at 46 °C produced the lowest final moisture content and SEC, while drying at 34 °C consumed the least energy per run. Temperature selection should reflect the moisture target, energy requirements, and product quality criteria. The FAST diagram clarifies each indicator's role in process evaluation. These descriptive conclusions apply to the tested conditions, and the SEC estimates depend on mass-balance consistency.

ADVANCED RESEARCH

Further research should evaluate the drying performance of Robusta coffee beans using a wider range of temperatures, drying durations, and batch sizes to identify optimal operating conditions. Future studies should also examine coffee quality characteristics, including sensory properties, chemical composition, and physicochemical changes after drying. Replication using larger experimental batches and direct measurement of energy consumption is recommended to improve the applicability of the findings to practical processing

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