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Analysis of Physical Characteristics of Coffee Beans Due to Variations in Drying Temperature and Cylinder Rotation Speed in A Rotary Dryer

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ABSTRACT: Controlling operating parameters during the drying process plays a crucial role in determining changes in the physical properties of coffee beans. This study examined the combined effect of drying temperature and cylinder rotation speed on the density and porosity of coffee beans in a rotary dryer system. Temperature variations were set at 40°C, 50°C, 60°C, and 70°C, while rotation speeds were varied by 5 rpm, 8 rpm, and 12 rpm. The evaluation was conducted to identify trends in changes in the internal structure of the beans in response to heat intensity and mechanical forces during the process. The results showed that increasing temperature contributed predominantly to the decrease in density, which was related to a reduction in water content and changes in the distribution of interparticle space within the bean matrix. At the same time, increasing rotation speed increased the opportunity for contact and movement between beans, thus accelerating the release of water vapor from the interior of the material. These conditions resulted in increased porosity values, especially at a combination of high temperature and 12 rpm rotation. Conversely, low temperature with 5 rpm rotation tended to maintain a higher structural density. The interaction of these two variables indicates that heat transfer and mechanical dynamics occur simultaneously in shaping the final physical characteristics of the product. In general, proper temperature and rotation speed settings are key factors in achieving stable and uniform drying results. These findings provide a technical basis for optimizing the rotary dryer-based coffee bean drying process.

KEYWORDS: Rotary dryer; drying temperature; cylinder rotation speed; density; porosity; coffee beans

I. INTRODUCTION

The coffee sector is a strategic commodity in the global agro-industrial system, whose sustainability is increasingly affected by climate change, energy dynamics, and demands for consistent product quality. Changes in environmental temperature and humidity patterns due to climate change have direct implications for production and post-harvest systems, including the coffee bean drying process, which requires precise control of thermal conditions [1]. In this context, drying is no longer viewed solely as a moisture reduction step, but as a thermal engineering process that determines the physical, chemical, and microstructural stability of food products.

Technically, coffee bean drying involves a complex simultaneous mechanism of heat and mass transfer, where a temperature gradient triggers the diffusion of water vapor from the internal parts to the surface of the material. This phenomenon is influenced by the equipment configuration, the distribution of hot air flow, and the mechanical interactions between particles during the process. Numerical studies of the hydrodynamics and heat transfer in rotary dryer systems indicate that gas-solid flow characteristics contribute significantly to uniform temperature distribution and drying efficiency [2]. Therefore, analysis of operational parameters such as temperature and rotation speed is crucial for understanding the structural dynamics of coffee beans during the drying process.

In a rotary dryer system, the cylinder rotation speed affects the material motion pattern, residence time, and the intensity of contact between the coffee beans and hot air. Variations in rotation will change the level of turbulence and the frequency of collisions between the beans, which in turn impacts the acceleration of water vapor release from the material's internal pores. Experimental and computational studies on fluidization and microwave-based drying processes indicate that changes in mechanical and thermal conditions can result in significant modifications to the quality attributes and structure of the material [3]. Thus, the setting of rotary dryer operating parameters plays a crucial role in controlling the physical transformation of coffee beans.

Drying temperature is the dominant variable determining the rate of evaporation and distribution of moisture content within the material. Increasing temperature tends to accelerate effective water diffusion, but under certain conditions can trigger internal stresses due to high moisture gradients. Research on thin-layer drying of Arabica coffee shows that controlling temperature and relative humidity significantly influences drying kinetics and final product quality [4]. Furthermore, a water vapor desorption system approach within a compression-cooling cycle also shows that the mechanism of water vapor release is strongly influenced by the thermodynamic characteristics of the material and the operating conditions of the system [5].

Changes in moisture content during drying are accompanied by volume changes and restructuring of the solid coffee bean matrix. These transformations affect the material's density and porosity, two physical parameters closely related to mechanical properties, storage stability, and response to subsequent processes such as roasting. Density reflects the particle density and internal void space, while porosity describes the proportion of void volume to the total material volume. Variations in these two parameters during drying indicate microstructural changes triggered by water movement and cellular tissue contraction.

Approaches to drying process intensification have been developed using various methods, including freeze-drying, spray-freeze drying, and the use of nanobubbles to improve the structural stability of instant coffee products [6,7]. Although these methods are effective in maintaining certain qualities, applications on a primary industrial scale, such as drying whole coffee beans, are still dominated by convective systems and rotary dryers due to energy efficiency and operational cost considerations. Therefore, optimizing parameters in rotary dryers is a realistic strategic alternative in the agro-industrial context.

On the other hand, the use of alternative energy sources for the drying process has attracted attention in recent years. The use of low-enthalpy geothermal heat pipe heat exchangers has been reported to significantly increase the efficiency of coffee drying systems [8]. A similar concept has also been applied to the tea leaf withering process, with results showing increased heat transfer efficiency and stable operating temperatures [9]. These findings underscore the importance of controlling thermal and mechanical parameters as key factors in ensuring drying system performance.

Although numerous studies have addressed the drying kinetics and chemical quality attributes of coffee, studies specifically examining changes in density and porosity in response to the combination of temperature and rotation speed in rotary dryers are limited. Yet, these two parameters have direct implications for product uniformity and post-processing efficiency. Experimental studies on microwave-fluidized bed drying have shown that changes in internal structure due to intensive heating can alter the shrinkage characteristics and pore distribution of the material [3]. This reinforces the urgency of a comprehensive analysis of the physical characteristics of coffee beans in conventional drying systems widely used in the field.

In addition to technical aspects, demands for energy efficiency and process sustainability also drive the need for an empirically data-based approach to optimizing operating parameters. In the context of a sustainable global food system, processing efficiency is one strategy to mitigate the impacts of climate change on the production chain [1]. Therefore, developing a rotary dryer operational model that considers changes in the material's physical properties during drying is relevant both scientifically and practically.

Based on this background, this research focuses on analyzing the physical characteristics of coffee beans due to variations in drying temperature and cylinder rotation speed in a rotary dryer. This study aims to evaluate trends in density and porosity changes as indicators of microstructural transformation during the drying process. With a systematic experimental approach, the research results are expected to contribute scientifically to enriching the literature on coffee bean drying engineering and provide a technical basis for optimizing operating parameters on an industrial scale. More broadly, these findings are expected to support the development of efficient, adaptive, and sustainable drying systems in line with the demands of the modern coffee agro-industry.

II. RESEARCH METHODS

This study used a quantitative experimental approach to analyze the effect of variations in drying temperature and cylinder rotation speed on changes in the density and porosity of coffee beans in a rotary dryer system. The study used a two-variable factorial design: drying temperature as the first variable and cylinder rotation speed as the second. Temperature variations were set at 40°C, 50°C, 60°C, and 70°C, while cylinder rotation speed varied at 5 rpm, 8 rpm, and 12 rpm. The combination of these two variables resulted in 12 treatment conditions that were tested independently.

The materials used in this study were coffee beans that had undergone an initial sorting process to ensure size uniformity and minimize the influence of morphological variations on the test results. Prior to the drying process, the initial moisture content of the coffee beans was measured using a standard oven method at 105°C to constant weight to obtain a wet basis moisture content value. Measurements were made using a digital scale with a precision of 0.01 g to ensure the accuracy of the mass data.

The main equipment used was a horizontal cylindrical rotary dryer with a convective air heating system (Figure 1). Hot air is generated by an electric heating unit equipped with a digital temperature controller with a tolerance of ±1°C. The cylinder rotation speed is controlled using an electric motor connected to an inverter to ensure stable rpm throughout the process. K-type thermocouples are placed at the air inlet and outlet to monitor temperature distribution during drying.

Each experiment was conducted with the same mass of starting material to maintain consistent test conditions. Coffee beans were loaded into the rotary dryer cylinder, then the system was run until the specified temperature was reached. The drying time was set until the moisture content approached safe storage conditions (±12% wet basis). During the process, samples were taken periodically to monitor mass changes and ensure stable operating parameters.

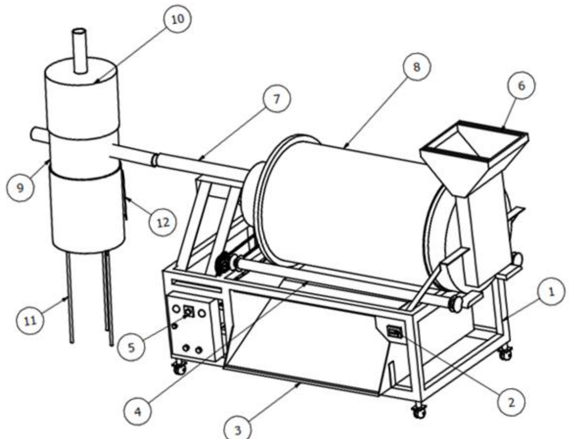

Figure 1. Rotary dryer machine, blowing air type, 1. Frame, 2. temperature control, 3. coffee bean ejector, 4. roll support, 5. motor rotation control, 6. turmeric slice input place, 7. hot air duct, 8. drying cylinder, 9. heat exchanger, 10. burner, 11. burner foot

Density measurements were performed using the volume displacement method. Bulk volume was determined by filling the material into a calibrated measuring cylinder without additional compaction. Bulk density was calculated using the equation:

$$\rho_b = \frac{m}{V_b} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where ρ_b is the density of coffee beans (kg/m³), m is the mass of coffee beans (kg), and V_b is the volume of coffee beans (m³).

To determine porosity, the true particle density was first calculated using the pycnometer method. Total porosity was then calculated using the equation:

$$\varepsilon = \left(1 - \frac{V_b}{V_t}\right) \text{ x } 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where ε is the porosity (%), V_b is the volume of coffee beans (kg/m³), and V_t is the total volume of the container (kg/m³).

III.RESULTS AND DISCUSSION

Figure 2 shows the relationship between drying temperature and coffee bean density at three different cylinder rotation speeds (5 rpm, 8 rpm, and 12 rpm). In general, all curves show a decreasing trend in density as the drying temperature increases from 40°C to 70°C. This pattern indicates that increasing temperature accelerates the evaporation of water from the bean's internal structure, resulting in a more dominant reduction in total mass compared to changes in volume. This phenomenon aligns with the principle of convective heat transfer, where increasing temperature increases the temperature gradient and accelerates the diffusion of water vapor from the interior of the material to the surface [2].

The decrease in density observed in the graph can also be attributed to changes in the coffee bean microstructure due to the loss of bound and free water. As the water content progressively decreases, the cellular network undergoes restructuring and the formation of microcavities due to internal vapor pressure. This condition causes an increase in pore volume relative to the remaining solid mass, resulting in a decrease in bulk density. This mechanism is consistent with reports that thermal drying triggers internal structural changes and non-uniform shrinkage in biomass-based materials [3].

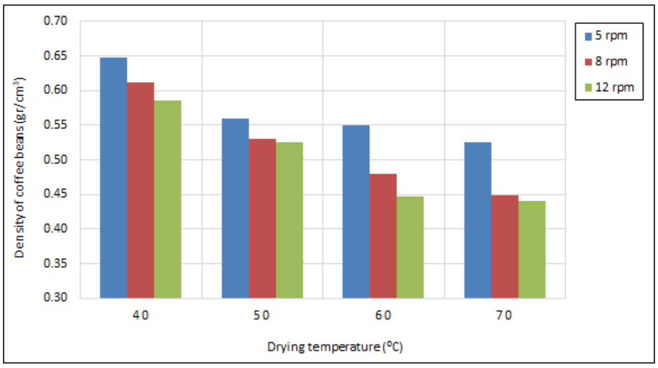

Figure 2. Graph of the relationship between drying temperature and coffee bean density

When comparing rotational speed variations, the highest density across the entire temperature range tends to occur at 5 rpm, while the lowest value is found at 12 rpm. This indicates that increasing the cylinder rotation speed strengthens the mechanical agitation effect and increases the frequency of collisions between the seeds. Higher collision intensity accelerates water vapor release by expanding the contact area between the seeds and the hot air, while also accelerating heat redistribution within the cylinder. This finding aligns with numerical studies of gas-solid dynamics in rotating systems, which indicate that increasing rotational speed increases mixing intensity and heat transfer efficiency [2].

In addition to mechanical factors, increasing temperature also contributes to accelerating the rate of water desorption from the solid matrix. The desorption process is influenced by the thermodynamic properties of the material and the operating conditions of the drying system, where higher temperatures increase the saturated vapor pressure and increase the driving force for evaporation [5]. Thus, the combination of high temperature and high rotational speed results in more intensive drying conditions, as reflected in the lower density values in the graph.

Figure 3 shows the relationship between drying temperature (40–70°C) and coffee bean porosity at three variations in rotary dryer cylinder rotation speeds (5 rpm, 8 rpm, and 12 rpm). In general, it can be seen that increasing the drying temperature tends to increase the porosity value, especially at lower rotation speeds. Increasing the temperature during the drying process is known to accelerate the process of water evaporation from within the material matrix, thus causing the formation of micro-cavities in the material's internal structure that contribute to increased porosity [4].

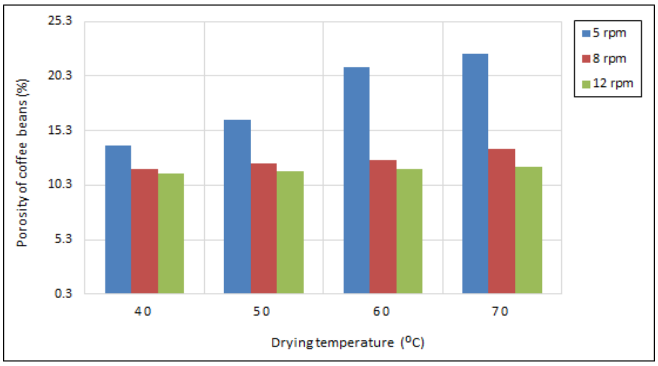

Figure 3. Graph of the relationship between drying temperature and coffee bean porosity

At a rotation speed of 5 rpm, coffee bean porosity increased significantly with increasing drying temperature. The porosity value increased from around 14% at 40°C to over 22% at 70°C. This increase indicates that higher temperatures accelerate the evaporation of water from within the coffee bean structure. As water escapes from the material matrix during the drying process, voids or micro-voids form within the bean structure, increasing porosity. [3] Furthermore, at a relatively low rotation speed, the coffee beans are in contact with the hot air in the drum for longer, resulting in more intensive heat and mass transfer. This allows for more effective water evaporation and the formation of more pores in the coffee bean structure.

At a rotation speed of 8 rpm, the porosity increase was still visible, but the increase was relatively more moderate compared to 5 rpm. The porosity value increased from around 11–12% at 40°C to around 14% at 70°C. This can be explained by the fact that increasing rotation speed shortens the material's residence time in the cylinder. Consequently, the time available for hot air to extract moisture from the coffee beans is more limited, resulting in less voids or pores within the material's structure than at lower rotation speeds.

Meanwhile, at a rotation speed of 12 rpm, the change in porosity with increasing temperature is relatively smaller and tends to be stable. Porosity values range from around 11–12% across all temperature variations. This indicates that at higher rotation speeds, the coffee beans experience faster movement within the cylinder, resulting in shorter contact time with the hot air. Furthermore, more intense movement also results in more even heat distribution, but the process of water evaporation from the inside of the beans is not maximized, thus limiting the formation of new pores in the material's structure.

Overall, this graph shows that drying temperature and cylinder rotation speed have a mutually reinforcing effect on changes in coffee bean porosity. Higher temperatures tend to increase porosity because they accelerate the diffusion and evaporation of water from within the material. However, increasing the cylinder rotation speed can reduce the porosity level, because it reduces the material's residence time in the drying chamber, so the process of removing water from the material matrix becomes less optimal. Therefore, setting operational parameters such as drying temperature and cylinder rotation speed is an important factor in controlling changes in the physical structure of coffee beans during the drying process [4,8].

CONCLUSIONS

This study shows that the drying temperature and rotation speed of the rotary dryer affect the density and porosity of coffee beans. Increasing the temperature from 40°C to 70°C causes a decrease in density at all rotation speeds. This occurs due to reduced moisture content and changes in the internal structure of the beans during the drying process. Higher rotation speeds, particularly 12 rpm, produce lower density values compared to 5 rpm and 8 rpm. This indicates that more intensive agitation accelerates the release of water vapor from the beans. Conversely, porosity values increase with increasing temperature and rotation speed, indicating the formation of more voids in the bean structure. In general, temperature is the main factor influencing changes in the physical properties of coffee beans, while rotation speed enhances the drying effect. Therefore, the correct combination of temperature and rotation speed is crucial for achieving the physical characteristics of coffee beans that suit the needs of subsequent processing.

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