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Moisture Content and Bean Weight Dynamics of the Parchment Arabica Coffee (*Coffea arabica* L.) Varieties During Sun Drying

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Abstract

Coffee post-harvest quality is highly dependent on drying, with sun drying being prevalent among smallholders. This method, however, is influenced by environmental factors and intrinsic bean properties. This study evaluated the moisture content and bean weight dynamics on parchment bean of six Arabica coffee varieties, namely Gayo 1, Gayo 2, K130, K29, S795, Sigarar Utang during natural sun drying in East Java, Indonesia. Beans were dried to a stable storage moisture, with periodic measurements of weight per fixed volume and gravimetric moisture content. Results showed that the drying follows a non-linear quadratic pattern (R^2 0.98–0.991), characterized by an initial rapid loss phase followed by a slower, diffusion-controlled phase. Significant varietal differences were observed in drying kinetics. Sigarar Utang dried fastest, reaching <12% moisture in 11–12 days, while other varieties required 15 days. Bean weight reduction was strongly correlated with moisture losses, providing a practical monitoring indicator. The findings conclude that drying behavior is variety-specific, influenced by bean morphology and parchment layer characteristics. Therefore, optimizing post-harvest practices requires consideration of these varietal traits to enhance efficiency, prevent over-drying, and maintain bean quality.

Keywords: *Coffea arabica* L., parchment coffee, sun drying, drying kinetics, varietal difference, moisture content, bean weight

INTRODUCTION

Coffee (*Coffea arabica* L.) is one of the most economically important plantation crops, widely cultivated for its high beverage quality and global market demand (Wintgens, 2012; Abreu *et al*., 2025). The sustainability of coffee production systems is closely linked to effective post-harvest handling, as inappropriate post-harvest practices may lead to quality deterioration and significant losses (Febrianto *et al*., 2023; Abreu *et al*., 2025). Among post-harvest operations, drying is a critical step that determines the physical stability, storability, and overall quality of coffee beans (Abreu *et al*., 2025).

In coffee post-harvest processing, beans are commonly handled and stored in the form of parchment coffee, in which the horn skin remains attached to the bean. This parchment layer provides mechanical protection and moderates moisture exchange with the surrounding environment (Clarke & Macrae, 2012; Phitakwinai *et al*., 2019), reducing the risk of physical damage and helping preserve bean quality during drying and storage. Because of these advantages, parchment coffee is widely used both for further processing and as planting material in many coffee-producing regions (Phitakwinai *et al*., 2019).

Sun drying remains one of the most widely applied drying methods for parchment coffee, particularly in smallholder-based production systems due to its low cost and minimum infrastructure requirements (Suherman *et al*., 2020; Hu *et al*., 2024; Abreu *et al*., 2025). However, sun drying is highly dependent on environmental conditions such as temperature, relative humidity, and solar radiation. These factors strongly influence drying rate and moisture removal efficiency, potentially resulting in non-uniform drying if not properly managed (Abreu *et al*., 2025). Consequently, understanding the drying behavior of parchment coffee under sun drying conditions is essential for improving post-harvest management practices.

Previous studies have shown that moisture reduction during coffee drying follows a non-linear pattern typical of agricultural product drying processes (Mujumdar, 2014; Abdissa *et al*., 2023; Valle-Vargas *et al*., 2021), characterized by rapid moisture loss at the early stages of drying followed by a slower, diffusion-controlled phase at later stages. This drying behavior has been consistently observed in parchment coffee subjected to different drying methods and environmental conditions (Phitakwinai *et al*., 2019; Valle-Vargas *et al*., 2021). Mathematical descriptions of drying behavior are often used to represent these patterns and to support the optimization of drying processes (Abdissa *et al*., 2023; Reyes-Chaparro *et al*., 2024; Valle-Vargas *et al*., 2021).

In addition to moisture content, bean weight decreases progressively during drying, primarily as a result of water evaporation (Brooker *et al*., 1992; Peñuela-Martínez *et al*., 2023). Changes in bean weight provide a practical indicator of moisture removal and drying progression. Simultaneous evaluation of moisture content and bean weight therefore offers a more comprehensive understanding of drying dynamics and facilitates identification of drying phases and appropriate drying endpoints (Peñuela-Martínez *et al*., 2023).

Drying behavior may also vary among coffee varieties, due to differences in bean size, density, and internal structure (Montagnon *et al*., 2003; Jordan, 2020) can affect moisture diffusion and drying rate. Drying kinetics of coffee beans are typically characterized by an initial rapid moisture removal phase followed by a falling-rate period controlled by internal moisture diffusion within the bean matrix (Nilnont *et al*., 2012; Fernando *et al*., 2025). Several studies have reported varietal differences in drying kinetics and moisture loss patterns of Arabica coffee when subjected to similar drying conditions (Valle-Vargas *et al*., 2021; Jordan, 2020). However, information regarding varietal differences in the drying behavior of Arabica parchment coffee under sun drying conditions, particularly in relation to simultaneous changes in moisture content and bean weight, remains limited.

Given the importance of parchment coffee in post-harvest handling and quality preservation, a clearer understanding of its drying behavior under sun drying conditions is required. Therefore, this study aims to evaluate the moisture content and bean weight dynamics of Arabica parchment coffee varieties (*Coffea arabica* L.) during sun drying, providing insight into general drying behavior as well as varietal responses under identical environmental conditions.

MATERIALS AND METHODS

The experiment was conducted from July to September 2021 at the Kaliwining Experimental Station, Jember, East Java, Indonesia. This period corresponds to the main dry season in the region and provides suitable environmental conditions for sun drying experiments under natural circumstances. Coffee bean samples were obtained from the Andungsari germplasm plantation, Bondowoso, East Java, located at approximately 1,000 m above sea level (asl.). Six Arabica coffee varieties were used in this study, namely Gayo 1, Gayo 2, K130, K29, S795, and Sigarar

Utang. These varieties were selected because they represent commonly cultivated and genetically diverse Arabica coffee in Indonesia. Coffee cherries were harvested using selective red cherry picking to ensure uniform maturity and minimize variability associated with ripeness.

Sun drying was carried out using an open sun drying method under natural environmental conditions. Parchment coffee beans were spread evenly in a single layer on drying trays to prevent excessive stacking and to promote uniform exposure to solar radiation and air circulation. During drying, the beans were turned periodically to ensure homogeneous moisture removal. For each observation, parchment coffee beans were weighed using a 5-liter container as a standardized volume unit to ensure consistent bulk handling during measurements. The container volume corresponds to approximately 0.005 m^3, and beans were loosely filled without compaction to maintain uniform bulk density conditions across measurements. This approach allowed consistent comparison of bean weight changes during the drying process while minimizing variation due to handling.

Drying was conducted daily during daylight hours and continued until the beans reached a stable moisture content suitable for safe storage. During the drying period, beans were protected from dew and rainfall by covering or relocating the trays when necessary. Bean weight was measured periodically throughout the drying process using a digital balance with appropriate precision. Weight measurements were taken at regular time intervals to capture the dynamics of weight reduction during drying. For each measurement, beans contained in the 5-liter container were weighed, and measurements were performed in triplicate.

Moisture content was determined using the standard gravimetric method. Subsamples of parchment coffee were oven-dried at a controlled temperature until constant weight was achieved. Moisture content was expressed as a percentage on a wet basis. All moisture determinations were conducted in triplicate to improve accuracy and reliability.

The experiment was arranged using a completely randomized design, with coffee variety as the main factor. Changes in bean weight and moisture content over drying time were analyzed descriptively and using regression analysis. Linear and quadratic regression models were fitted to describe the relationship between drying time and both bean weight and moisture content. The goodness of fit of each model was evaluated using the coefficient of determination (R^2).

Correlation analysis was performed to examine the relationship between moisture content reduction and bean weight loss during the drying process. All statistical analyses were conducted using standard statistical software, and results were interpreted descriptively and comparatively across coffee varieties.

RESULT AND DISCUSSION

General Drying Behavior of Arabica Parchment Coffee under Sun Drying

Based on averaged data across all varieties and replicates, sun drying resulted in a continuous and coordinated reduction in both moisture content and bean weight throughout the drying period (Figure 1). At the beginning of drying (day 1), the average moisture content was approximately 52.84%, accompanied by an average bean weight of 3.70 kg. These values reflect typical conditions of freshly processed coffee beans with high water content that must be reduced to ensure safe storage.

A rapid decline in moisture content occurred during the early drying stage. As shown in

Figure 1a, average moisture content decreased sharply from 52.84% on day 1 to approximately 41.41% by day 5. This initial phase accounted for a large proportion of total moisture loss and coincided with a substantial reduction in average bean weight from 3.70 kg to approximately 3.00 kg (Figure 1b). The pronounced decreases observed during this stage indicate the dominance of surface evaporation and the removal of free and weakly bound water under direct solar exposure.

During the intermediate drying stage (days 6–10), the rate of moisture reduction gradually decreased. Average moisture content declined from about 37.65% on day 6 to approximately 19.13% on day 10, while average bean weight decreased from 2.86 kg to around 2.36 kg. The slower rate of reduction observed in both variables suggests a transition from surface-controlled evaporation to internal moisture diffusion as the primary mechanism governing water movement. At this stage, moisture transport becomes increasingly constrained by the internal structure of the bean, resulting in greater resistance to further moisture loss.

In the later drying stage (days 11–15), moisture content approached levels considered safe for storage of green coffee beans. Average moisture content declined from approximately 17.66% on day 11 to about 8.33% by day 15, while average bean weight decreased more gradually from around 2.38 kg to approximately 2.09 kg. The flattening of both moisture and weight reduction curves during this phase indicates that bound water dominated the drying process and that further moisture removal occurred at a much slower rate due to diffusion limitations within the bean matrix. Quadratic regression models fitted to the averaged data adequately described the temporal trends of both moisture content and bean weight (Figure 1a and 1b). The non-linear shape of the fitted curves captured the rapid initial reductions followed by progressively slower changes at later stages, confirming that the drying process did not proceed at a constant rate. The similar curvature observed for both variables indicates that bean weight reduction closely followed moisture loss dynamics.

Varietal differences in drying behavior

Figure 2 presents the moisture reduction patterns of six Arabica parchment coffee varieties during sun drying, while Table 2. summarizes moisture contents at the initial, intermediate, and final stages of drying, along with drying duration and regression performance. All varieties exhibited a continuous decrease in moisture content throughout the drying period, confirming that sun drying effectively reduced moisture to levels suitable for safe storage. However, the rate and timing of moisture reduction differed significantly among varieties.

At the initial stage (day 0), moisture content ranged from 52.17% to 53.84%, with small but statistically significant differences among varieties. Despite these differences, the overall initial moisture range was relatively narrow, indicating comparable starting conditions across all samples. Therefore, subsequent differences in drying behavior were primarily associated with inherent varietal characteristics rather than initial moisture content. Similar observations have been reported in previous studies emphasizing that internal moisture diffusion and bean characteristics become dominant factors during the later stages of coffee drying (Fernando *et al.*, 2025; Largo-Avila *et al.*, 2023). By the intermediate stage (day 7), varietal differences became more pronounced. Sigarar Utang showed the lowest mid-stage moisture content (26.68%), significantly lower than all other varieties, indicating a faster moisture reduction during the early to mid drying phase. In contrast, K29 retained the highest moisture content (37.28%), followed by Gayo 2 and S795, suggesting a slower

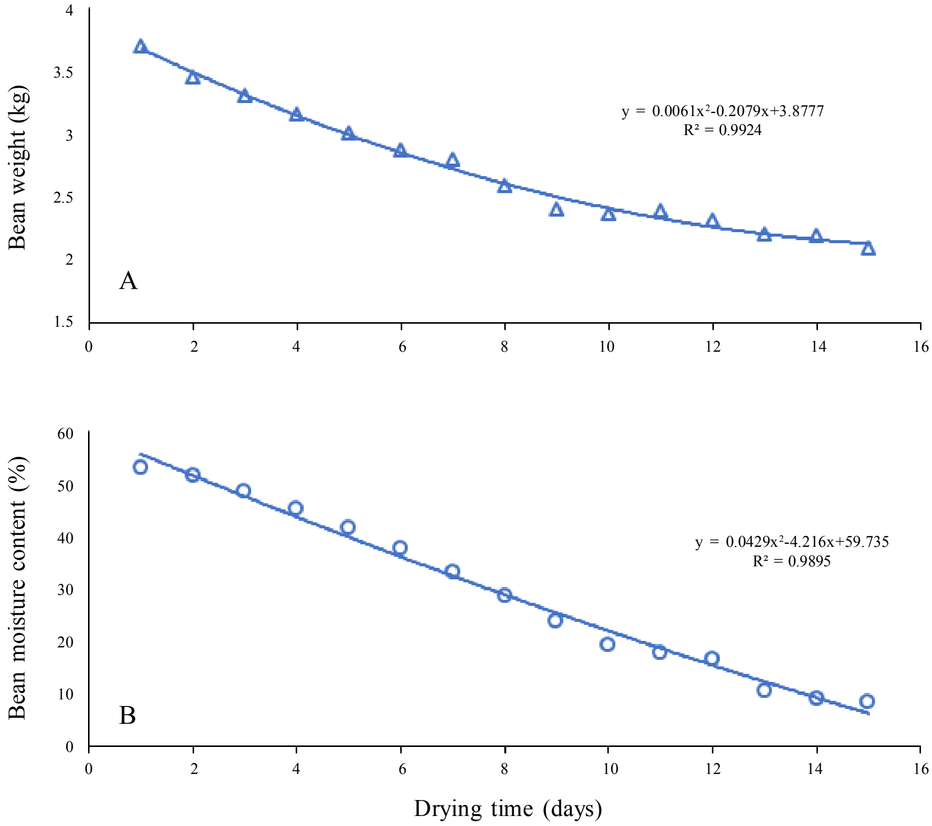

Figure 1. General drying behavior of coffee beans during sun drying based on averaged data across all varieties and replicates : (a) Average moisture content reduction over drying time with quadratic regression; (b) Average bean weight reduction over drying time with quadratic regression

internal moisture diffusion process. These differences are clearly reflected in the curvature and slope of the drying curves shown in Figure 2. According to Coradi *et al.* (2016), such differences in drying rate are commonly linked to variations in bean density, structural arrangement, and resistance to internal moisture movement. At the final stage (Day 15), all varieties except Sigarar Utang reached moisture contents within a narrow range of approximately 8.0–8.8%, which is generally considered safe for storage of parchment coffee. Sigarar Utang reached moisture content below 12% earlier, requiring only 11–12 days, whereas the remaining varieties required the full 15 days. This result highlights a clear varietal effect on drying duration and suggests that applying a uniform drying time across varieties may increase the risk of over-drying for faster-drying cultivars.

Regression analysis demonstrated that a quadratic model provided the best fit for moisture reduction across all varieties, with coefficients of determination (R^2) ranging from 0.98 to 0.991. The consistently high R^2 values indicate a strong non-linear relationship between drying time and moisture content. This non-linearity reflects the typical drying behavior of parchment coffee, characterized by rapid removal of free water at high moisture levels followed by a slower, diffusion-controlled phase as moisture content decreases. Similar drying kinetics have been widely reported for coffee and other hygroscopic agricultural products (Coradi *et al.*, 2016).

The observed varietal differences in moisture reduction are likely associated with differences in bean morphology and parchment layer characteristics, which directly influence internal moisture diffusion resistance. The parchment layer acts as a semi-permeable barrier that regulates moisture transfer from the endosperm to the bean surface (Farah, 2012). Varieties with lower diffusion resistance, such as Sigarar Utang, exhibited faster drying and shorter drying durations, whereas varieties with higher resistance required longer drying periods to reach similar moisture levels.

Figure 3 shows the relationship between seed moisture content and bean weight measured per 5 L container during the sun drying of Arabica parchment coffee. The results indicate a strong positive association between moisture content and bean weight, where decreasing moisture content was consistently accompanied by a reduction in bulk bean weight within a fixed container volume. This confirms that water loss was the primary factor governing mass reduction during drying.

At high moisture levels (above approximately 45%), bean weight per container was relatively high and clustered within a narrow range. During this stage, the mass of parchment coffee was strongly influenced by the presence of free and weakly bound water, resulting in substantial weight reduction even with relatively small decreases in moisture content. Similar behavior has been reported in studies on coffee drying kinetics, where early-stage moisture loss contributes disproportionately to mass reduction (Nilnont *et al.*, 2012).

As moisture content decreased to intermediate levels (approximately 25–40%), the relationship between moisture content and bean weight became more dispersed, although the overall trend remained positive. Bean weight declined progressively with decreasing moisture content, but the rate of mass reduction per unit decrease in moisture content was reduced. This pattern reflects a transition from surface evaporation to diffusion-controlled moisture transport from the interior of the bean, as described for parchment coffee and other hygroscopic agricultural materials (Phitakwinai *et al.*, 2019).

At low moisture levels (below approximately 15%), bean weight approached a relatively stable range, despite continued decreases in moisture content. This flattening of the moisture–weight relationship indicates that most removable water had already been lost and that remaining moisture was strongly bound within the bean matrix. Consequently, further moisture loss produced only minor changes in container weight. Similar stabilization of mass near equilibrium moisture content has been observed in previous studies on coffee beans and related products (Araujo *et al.*, 2021).

Table 2. Moisture reduction characteristics of Arabica parchment coffee varieties during sun drying

Variety	Initial moisture (%)(Day 0)	Mid moisture (%)(Day 7)	Final moisture (%)(Day 15)	Drying duration to <12% (days)	Best-fit model	R^2
Gayo 1	53.38 b	34.45 c	8.11 cd	15	Quadratic	0.988
Gayo 2	53.84 a	35.16 b	8.35 bc	15	Quadratic	0.991
K130	52.23 d	29.53 d	8.81 a	15	Quadratic	0.991
K29	52.59 cd	37.28 a	8.38 b	15	Quadratic	0.980
S795	52.82 c	35.14 b	8.00 d	15	Quadratic	0.991
Sigarar Utang	52.17 d	26.68 e	-	11–12	Quadratic	0.980

Note: Values followed by different letters within the same column indicate significant differences among varieties based on Tukey with (ANOVA, $p < 0.05$).

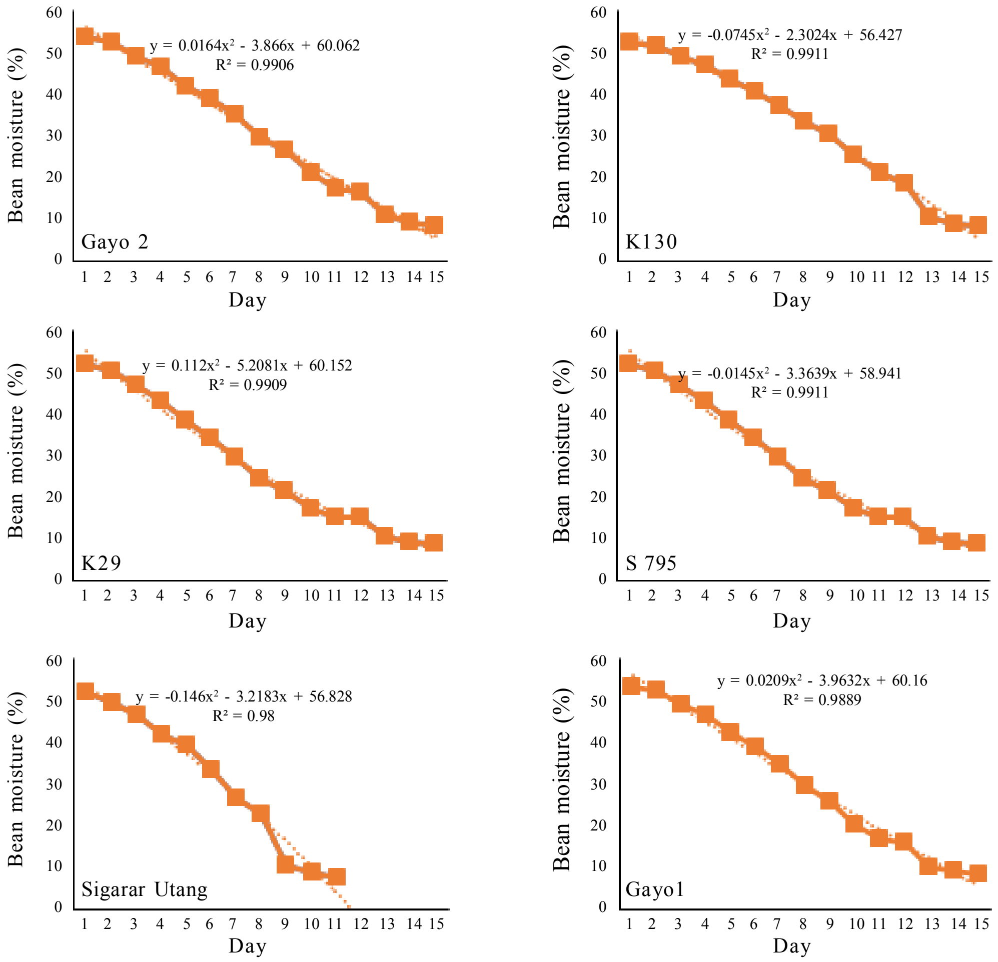

Figure 2. Moisture content changes of six Arabica parchment coffee varieties during sun drying, showing non-linear drying patterns and varietal differences in drying rate

The overall distribution of data points reveals a non-linear relationship between seed moisture content and bean weight per container volume. While the correlation between the two variables is strong, the relationship is not linear across the entire moisture range. Instead, the slope of the relationship decreases as drying progresses, reflecting changes in moisture binding strength and internal diffusion resistance. This behavior is consistent with numerical and experimental studies on moisture migration and shrinkage during coffee drying (Nilnont *et al*., 2012).

The use of a fixed container volume (5 L) provides additional insight into bulk behavior during drying. As moisture content decreases, changes in bean weight reflect not only water loss but also variations in bulk density and packing arrangement caused by bean shrinkage and structural adjustment (Sfredo *et al.*, 2016; Araujo *et al*., 2021). Previous research has demonstrated that moisture reduction is closely associated with changes in physical and aerodynamic properties of coffee beans, which directly affect bulk density and mass per unit volume (Araujo *et al*., 2021; Caporaso *et al*., 2018).

From a practical standpoint, the strong association between moisture content and bean weight per container suggests that bulk weight measurements can be used as a rapid and

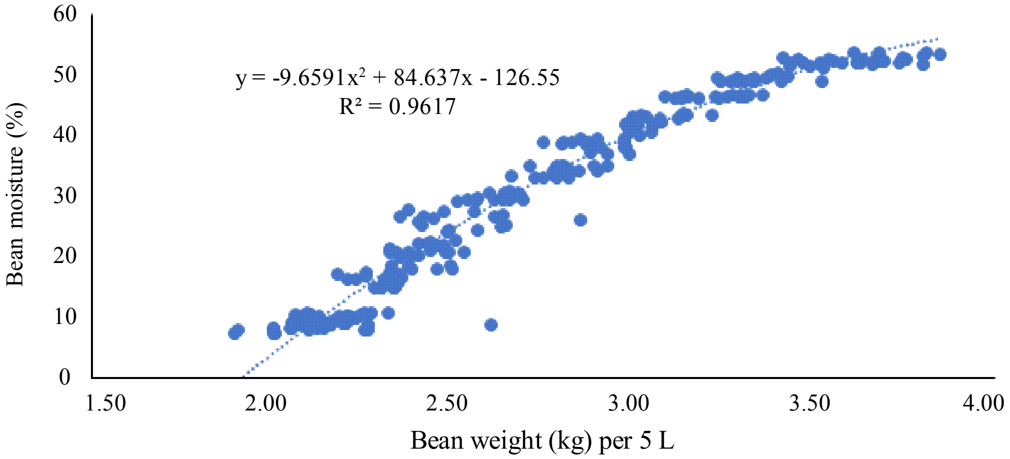

Figure 3. Scatter plot showing the relationship between bean moisture content and bean weight per 5 L container during sun drying of parchment Arabica coffee

indirect indicator of drying progress, particularly during the early and intermediate drying stages. However, at low moisture contents, reliance solely on container weight may lead to underestimation of remaining moisture, as weight changes become minimal despite continued moisture loss. Therefore, bulk weight monitoring should be complemented with direct moisture measurement to ensure accurate determination of the drying endpoint.

CONCLUSION

Based on the results of this study, it can be concluded that:

1. Sun drying of Arabica parchment coffee exhibits a consistent non-linear pattern, with a rapid phase of moisture content and bean weight reduction at the beginning, followed by a slower, diffusion-controlled phase at lower moisture levels. Quadratic mathematical models effectively represent this drying behavior.
2. There are significant differences in drying responses among Arabica coffee varieties. The Sigarar Utang variety showed the highest drying rate and shortest drying duration, while the K29 variety was the slowest. These differences indicate the influence of variety-specific bean morphological and physiological properties, such as parchment layer thickness or permeability and internal water diffusion resistance.
3. The reduction in bean weight per fixed container volume has a close and positive relationship with moisture loss, making it a practical indicator for monitoring drying progress. However, this relationship is non-linear, where the weight loss per unit of moisture loss decreases as the beans approach a safe storage moisture level.

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