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Posted Date: 21 April 2026

doi: 10.20944/preprints202604.1470.v1

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Abstract

The performance of grain storage silos is strongly influenced by discharge flow patterns, hopper geometry, and material properties such as moisture content and impurity levels. However, the combined effects of these factors on flow behavior, discharge rate, and segregation are not yet fully understood. This study experimentally investigated the integrated effects of moisture content, prismatic hopper geometry (hopper angle β), and impurity addition on flow behavior, segregation, and mass flow rate in reduced-scale silos. Experiments were conducted using three prismatic silos with hopper angles of $\beta = 15°$, 33°, and 45°, filled with maize at moisture contents of 13.6%, 20.2%, and 26.0% (wet basis), under both clean conditions and with the addition of 10% impurities (fraction passing through a 5 mm sieve). The discharge rate was determined by direct mass–time measurements, flow patterns were inferred from video analysis, and segregation was quantified based on the mass fraction of impurities in samples collected during discharge. The results indicate that moisture content was the most influential factor, reducing the discharge rate by up to 22.8% when increasing from 20.2% to 26.0% w.b. ($p < 0.05$). Hopper geometry also had a significant effect, with performance differences among configurations becoming more pronounced under high-moisture conditions. The addition of 10% impurities increased the discharge rate under all tested conditions, with gains of up to 29.0% at 26.0% w.b. and $\beta = 15°$. Segregation intensified with increasing moisture content, leading to a progressive accumulation of impurities toward the end of discharge. The stick-slip phenomenon was observed under a critical condition (26.0% w.b., $\beta = 15°$, with impurities), resulting in a 23.0% reduction in average discharge rate compared to the equivalent stable condition. These findings demonstrate that granular flow behavior in silos is governed by the interaction between moisture, hopper geometry, and material composition. The results also suggest that operational strategies such as pre-cleaning should be evaluated in conjunction with expected moisture conditions, as pre-cleaning may adversely affect flow performance under high-moisture scenarios.

Keywords: granular flow; discharge rate; hopper geometry; segregation; moisture content; maize

1. Introduction

Grain storage is a critical component of the agricultural supply chain, and silo discharge performance directly affects logistical efficiency, operational costs, and product quality. In high-production scenarios, such as the 119.56 million tons projected for Brazil in the 2025/26 season, post-harvest infrastructure often operates at its limits. Under these conditions, the occurrence of blockages, stagnant zones, or unstable flow reduces operational availability, increases energy consumption, and raises the risk of product deterioration [1]. The flow behavior of grains during discharge is therefore considered a critical parameter in silo design and operation [2].

Silos used for maize storage present different geometric configurations, with pyramidal hoppers being characteristic elements of square or rectangular metal silos widely used in agriculture [3]. The hopper inclination, defined by the angle β relative to the vertical, is a key geometric parameter that, together with material friction properties (internal friction and wall–particle friction), determines the flow pattern during discharge [4]. The theory established by Jenike [2] distinguishes between mass flow, in which the entire bulk material is mobilized during discharge, eliminating stagnant zones and ensuring a first-in–first-out sequence, and funnel flow, characterized by the formation of a central flow channel while material near the walls remains stagnant.

The flow regime directly affects both the structural stability of the silo and the quality of the stored product. In mass flow, complete mobilization of the bulk reduces segregation and product degradation during prolonged storage [5]. In contrast, funnel flow promotes segregation, localized deterioration, and the development of asymmetric loads that may compromise structural integrity [2,6]. Experimental and modeling studies have established that the transition between these flow regimes depends on the combined effects of hopper angle (β) and wall friction properties, which define the conditions under which mass flow or funnel flow is expected to occur in planar geometries [6]. Design criteria based on these relationships have been formalized in standards such as the Eurocode [7], which provide boundaries for predicting flow regimes as a function of geometric and material parameters. Recent numerical studies have validated these criteria for predicting flow patterns in silos [17].

Flow quality is determined not only by silo geometry but also by the physical properties of the stored material. Particle size distribution, grain shape, and the presence of impurities affect internal friction, cohesion, and segregation tendency [9]. Materials with high sphericity and narrow size distribution tend to reduce interparticle friction and improve flowability, whereas the presence of broken grains and fines increases heterogeneity and may lead to zones of higher resistance to flow [10]. Storage conditions, particularly ambient humidity, can further influence material behavior through water absorption and the formation of capillary bridges [11].

An increase in moisture content promotes the formation of capillary bridges between particles, increasing apparent cohesion. This results in higher characteristic angles (such as angle of repose and internal friction angle) and reduced flowability [11]. In particulate maize systems (e.g., flour and grits), reduced flowability has been observed with increasing moisture [10], while in whole maize grains (Zea mays), direct mechanical changes such as increased cohesion and altered internal friction have also been reported [6]. From a design perspective, increased cohesion shifts operating conditions, increasing the critical outlet size required to ensure flow and promoting funnel flow, arching, and ratholing, even in geometries initially considered adequate [2,6].

The mass discharge rate of granular materials under quasi-steady conditions has been widely investigated, with classical models relating discharge behavior to material properties and outlet geometry [12]. However, for agricultural materials, factors such as grain shape, particle size variability, and especially moisture-induced cohesion significantly influence flow behavior, limiting the direct applicability of these classical approaches. As a result, the average discharge rate becomes a practical and robust parameter for comparing different operating conditions in real systems [13].

The presence of impurities and broken grains introduces granulometric variability into the granular medium, affecting both flowability and segregation during filling and discharge. Mechanisms such as trajectory segregation, percolation, and impact redistribute particles according to size and density, concentrating fines and fragments in specific regions of the silo, typically near the center during filling [8,9]. This heterogeneous distribution alters porosity and airflow paths, increasing resistance to aeration and creating zones of higher thermal and hygroscopic risk, which may lead to deterioration [8]. In practice, pre-cleaning and moisture control are commonly adopted strategies to mitigate these effects [12,13].

The stick-slip phenomenon is particularly relevant in hoppers prone to funnel flow and in materials with moderate cohesion, frequently observed during the discharge of moist grains or materials with a high fraction of fines [14]. This phenomenon consists of cyclic oscillations in discharge velocity, alternating between periods of stagnation (stick) and sudden movement (slip). Its physical origin is associated with the formation and collapse of arches above the outlet [20]. During the stick phase, stresses redistribute within the granular mass, leading to the formation of a cohesive arch capable of supporting the material above; once stresses exceed its mechanical resistance, collapse occurs (slip phase), releasing a discrete volume of material [20]. In agricultural materials, moisture intensifies this behavior due to increased capillary cohesion [10].

The technical literature on silo flow extensively addresses the isolated effects of hopper geometry [2,4,7], moisture content [6,11], and impurities [8,9], generally as separate topics. Studies focusing on material characterization report particle size distributions and repose angles, while flow-oriented research investigates discharge patterns and rates, and storage-focused studies emphasize segregation and deterioration. Although valuable, these approaches do not integrate product properties, geometry, and flow behavior into a unified framework that allows direct comparison across conditions, especially when different methods and instruments are used.

In this context, existing studies do not provide an integrated approach that connects material properties (moisture and impurities), geometric parameters (hopper angle), and flow behavior (discharge rate, flow regime, and segregation) within a single experimental framework. This fragmentation limits the ability to compare silo configurations and operating conditions using a unified criterion, highlighting the need for a structured experimental approach.

This study focuses on reduced-scale prismatic silos with different hopper angles ($\beta = 15°$, 33°, and 45°), using maize as a granular material. These configurations are representative of metal silos widely used in agriculture and allow the investigation of fundamental flow mechanisms under controlled conditions. The selected moisture range (13.6% to 26.0% wet basis) and impurity fraction (10%) represent typical conditions encountered in storage facilities, particularly in tropical regions where high-moisture maize is frequently received [1].

This study aims to systematically investigate the combined effects of hopper geometry, moisture content, and impurity fraction on the flow behavior of maize in prismatic silos. Specifically, the objectives are: (i) to quantify the effect of moisture content on mass discharge rate; (ii) to evaluate the influence of hopper angle on flow regime and discharge performance; (iii) to assess the impact of impurity addition on discharge rate and segregation patterns; and (iv) to identify and characterize the occurrence of slip–stick behavior under critical conditions.

2. Materials and Methods

2.1. Samples and Material Preparation

A single batch of 80 kg of maize (Zea mays) with an initial moisture content of 13.6% (wet basis) was obtained from the Agricultural Products Processing Research Center (CPPPA) at the Federal University of Lavras (UFLA).

Impurities (broken grains, fragments, and light material) were obtained from the same batch by sieving, considering the fraction passing through a 5 mm mesh sieve. For the tests involving impurities, a fraction corresponding to 10% (by mass) was added to the clean maize, followed by manual mixing until a visually uniform distribution was achieved.

Moisture content was adjusted to nominal levels of 20% and 26% (wet basis) by controlled spraying of distilled water using a manual sprayer equipped with a fine mist nozzle. After water addition, the material was manually homogenized to promote uniform moisture distribution.

The amount of water added was determined based on a mass balance, considering the initial and target moisture contents.

Moisture content was verified in triplicate for each experimental condition using two complementary methods:

- **Oven method:** samples of approximately 10 g were dried in a forced-air oven at 105 ± 3 °C for 24 h, following ISO 6540 recommendations for maize;

doi:10.20944/preprints202604.1470.v1

- **Portable moisture meter:** a portable device (iBoa A2456, range 0–40% w.b.) was used for immediate verification during experiments.

Final moisture values were expressed as mean ± standard deviation, resulting in 13.6 ± 0.2%, 20.2 ± 0.3%, and 26.0 ± 0.4% (wet basis).

2.2. Experimental Units: Reduced-Scale Silos

Three reduced-scale prismatic silo models were constructed using 12 mm thick Medium Density Fiberboard (MDF) panels, with different hopper inclination angles (β = 15°, 33°, and 45°).

MDF was selected as the wall material due to its smooth and uniform surface, enabling accurate geometric reproduction and consistent wall–particle interaction conditions across experiments.

A schematic representation of the silos, including their main dimensions and the physical models used in the experiments, is shown in Figure 1. The hopper inclination angle (β), defined relative to the vertical, is illustrated in Figure 2.

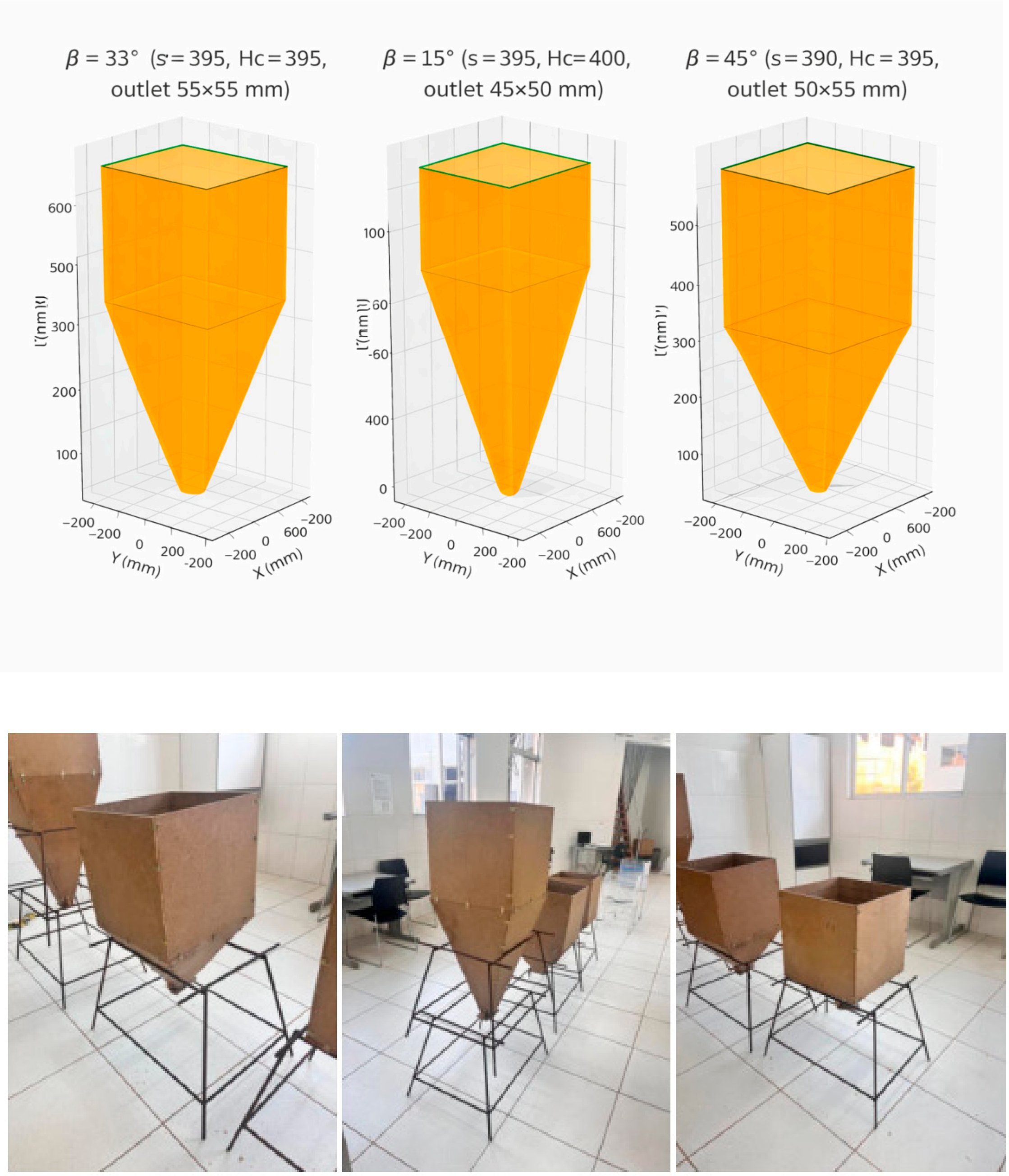

Figure 1. Schematic representation of the reduced-scale prismatic silos and experimental setup.

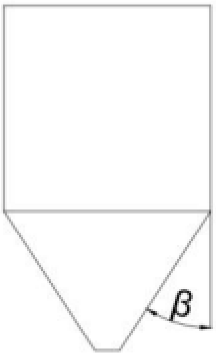

Figure 2. Definition of hopper inclination angle (β) relative to the vertical axis.

The internal dimensions and geometric characteristics of the silos are presented in Table 1.

Table 1. Dimensions and geometric characteristics of the prismatic silos used in the experiments.

Parameters	**Silo β = 15°**	**Silo β = 33°**	**Silo β = 45°**
Body dimensions (mm)	390 × 395 × 400	390 × 395 × 395	400 × 390 × 395
Outlet dimensions (mm)	45 × 50	55 × 55	55 × 50
Outlet area (mm^2)	2250	3025	2750
Total internal volume (m^3)	0.0988	0.0773	0.0714
Total silo height (mm)	650	645	640
Wall material	MDF (12 mm)	MDF (12 mm)	MDF (12 mm)

The silos have a prismatic cross-section representative of square metal silos commonly used for grain storage. Their dimensions were defined to allow manual operation, sample collection, and visual observation of flow behavior, while preserving geometric proportions relevant to the physical phenomena under investigation.

2.3. Experimental Procedure

The experiment followed a full factorial design (3 × 3 × 2), resulting in 18 treatments with three independent replicates each (total of 54 tests).

The evaluated factors and levels were:

- Hopper angle (β): 15°, 33°, and 45°;
- Moisture content: 13.6%, 20.2%, and 26.0% (wet basis);
- Purity condition: clean maize (0% impurities) and maize with 10% impurities.

The complete experimental matrix is presented in Table 2.

Table 2. Experimental design matrix with 18 treatments (3 × 3 × 2 factorial design).

Table	1.	Impurities (%)	Hopper Angle β (°)
T1	13.6	0	15
T2	13.6	0	33
T3	13.6	0	45
T4	13.6	10	15
T5	13.6	10	33
T6	13.6	10	45
T7	20.2	0	15
T8	20.2	0	33
T9	20.2	0	45
T10	20.2	10	15
T11	20.2	10	33
T12	20.2	10	45
T13	26.0	0	15
T14	26.0	0	33
T15	26.0	0	45
T16	26.0	10	15
T17	26.0	10	33
T18	26.0	10	45

For each test, the silo was positioned on a leveled surface and manually filled to the top. The surface of the granular material was leveled using a straightedge to ensure a uniform and reproducible initial condition. The total loaded mass (m_{total}) was recorded using a platform scale with digital indicator (Ramuza DS-1000, capacity 200 kg, resolution 0.01 kg).

Discharge was initiated by the full and instantaneous opening of a guillotine-type gate located at the hopper outlet. Simultaneously, a digital stopwatch (resolution 0.01 s) was started to measure the total discharge time (t_f), defined as the interval between gate opening and complete cessation of material flow.

The entire discharge process was recorded using a smartphone camera (1080p resolution, 30 frames per second) positioned above the silo, with a field of view covering the entire top surface. The recordings were subsequently analyzed to classify flow regimes and identify phenomena such as stagnant zones and stick-slip phenomenon behavior.

During discharge, five sequential samples were collected at equally spaced time intervals, defined as:

$$tj = j \cdot \frac{tf}{6}, for\ j = 1, 2, \ldots, 5. \qquad (3)$$

The masses of maize ($m_{maize,j}$) and impurities ($m_{imp,j}$) in each sample were recorded to calculate the impurity mass fraction, defined as:

$$fj = \frac{m_{imp,j}}{m_{imp,j} + m_{maize,j}} \qquad (4)$$

where fj is the impurity fraction at time tj, with reference values of $f0$=0,10 for tests with impurities and $f0$=0 for clean maize.

Flow regime classification was performed based on visual analysis of the recorded videos, using the following criteria:

- **Mass flow:** approximately uniform and horizontal lowering of the entire top surface, with no visible stagnant regions near the walls;
- **Funnel flow:** formation of a stable central depression, with material remaining apparently stagnant near the walls during most of the discharge;
- **Mixed flow:** transition during discharge, initially resembling mass flow and evolving toward funnel flow behavior.

Occurrences of temporary blockages, arch formation, and stick-slip events were recorded in a dedicated log, including time of occurrence and qualitative description of the observed behavior.

Between replicates, all equipment and utensils (sieves, trays, containers, and silo interiors) were carefully cleaned using a brush and dry cloth to remove residual material, ensuring independence between experimental runs.

2.4. Statistical Analysis

The average mass discharge rate for each test was calculated as:

$$q = \frac{m_{total}}{tf} \qquad (5)$$

where q is the average discharge rate (kg·s^{-1}), m_{total} is the total discharged mass (kg), and tf is the total discharge time (s).

Discharge rate and impurity fraction data were analyzed using factorial analysis of variance (ANOVA) to evaluate the main effects of the studied factors (moisture content, hopper angle, and impurity presence), as well as their first- and second-order interactions. The statistical model adopted was:

$$Yijkl = \mu + \alpha i + \beta j + \gamma k + (\alpha\beta)ij + (\alpha\gamma)ik + (\beta\gamma)jk + (\alpha\beta\gamma)ijk + \varepsilon ijkl \qquad (6)$$

where $Yijkl$ is the response variable (discharge rate or impurity fraction), μ is the overall mean, αi\alpha_iαi is the effect of the iii-th level of moisture content, βj is the effect of the j-th hopper angle, γk is the effect of the k-th level of purity condition, $(\alpha\beta)ij$, $(\alpha\gamma)ik$, $(\beta\gamma)jk$e $(\alpha\beta\gamma)ijk$ represent interaction effects, and $\varepsilon ijkl$ is the random error associated with the lll-th replicate.

When significant effects were identified ($p < 0.05$), treatment means were compared using Tukey's test at a 5% significance level.

For the analysis of temporal segregation (*fj* over discharge time), a linear mixed-effects model was applied, considering time as a within-subject factor and experimental run as a random effect.

All statistical analyses were performed using R software (version 4.3.1), with the *agricolae* package for mean comparisons and the *nlme* package for mixed-effects modeling.

3. Results

3.1. Experimental Characterization and Statistical Analysis

The analysis of variance (ANOVA) for mass discharge rate revealed statistically significant effects ($p < 0.05$) for all main factors, as well as for the interaction between moisture content and hopper angle. The complete ANOVA summary is presented in Table 3.

Table 3. Analysis of variance (ANOVA) for mass discharge rate ($kg \cdot s^{-1}$).

Source of Variation	Sum of Squares	df	Mean Square	F-value	p-value
Moisture (U)	0.845	2	0.4225	33.95	< 0.001
Hopper angle (β)	0.525	2	0.2625	21.09	< 0.001
Purity (P)	0.148	1	0.1480	11.89	0.0015
U × β	0.232	4	0.0580	4.66	0.0039
U × P	0.042	2	0.0210	1.69	0.1993
β × P	0.038	2	0.0190	1.53	0.2310
U × β × P	0.056	4	0.0140	1.13	0.3601
Residual	0.448	36	0.0124	–	–
Total	2.334	53	–	–	–

Moisture content was the most influential factor ($F = 33.95$; $p < 0.001$), followed by hopper angle ($F = 21.09$; $p < 0.001$) and impurity presence ($F = 11.89$; $p = 0.0015$). The significant interaction between moisture content and hopper angle (U × β; $F = 4.66$; $p = 0.0039$) indicates that the effect of hopper geometry on discharge rate depends on the moisture level of the maize, and vice versa.

In contrast, the interactions between moisture and purity (U × P), hopper angle and purity (β × P), and the three-way interaction (U × β × P) were not statistically significant ($p > 0.05$), suggesting that, within the studied range, the effect of impurities on discharge rate was relatively consistent across moisture levels and hopper configurations.

The mean comparisons obtained by Tukey's test ($p < 0.05$) are presented in Table 4.

doi:10.20944/preprints202604.1470.v1

Table 4. Mean discharge rate ($kg \cdot s^{-1}$) and Tukey grouping ($p < 0.05$) for the main factors.

Factor	**Level**	**Mean ($kg \cdot s^{-}$.**	**Group** [1]
Moisture (% w.b.)	13.6	1.066 ± 0.042	a
	20.2	1.040 ± 0.038	a
	26.0	0.823 ± 0.035	b
Hopper angle β (°)	15	1.092 ± 0.041	a
	33	1.000 ± 0.039	b
	45	0.608 ± 0.036	c
Purity	With impurities (10%)	1.002 ± 0.037	a
	Without impurities (0%)	0.926 ± 0.034	b

[1] Means followed by the same letter within each factor do not differ statistically according to Tukey's test ($p > 0.05$).

The Tukey test results (Table 4) indicate that moisture levels of 13.6% and 20.2% did not differ significantly, while both differed from 26.0% (w.b.), which resulted in the lowest average discharge rate ($0.823\ kg \cdot s^{-1}$).

For hopper geometry, all evaluated angles (15°, 33°, and 45°) showed statistically significant differences, with $\beta = 15°$ producing the highest discharge rate ($1.092\ kg \cdot s^{-1}$) and $\beta = 45°$ the lowest ($0.608\ kg \cdot s^{-1}$).

The presence of 10% impurities significantly increased the discharge rate ($1.002\ kg \cdot s^{-1}$) compared to clean maize ($0.926\ kg \cdot s^{-1}$).

3.2. Effect of Moisture Content on Discharge Rate

Moisture content had a pronounced effect on the mass discharge rate of maize, as confirmed by the ANOVA results (Table 3). As shown in Table 4, increasing moisture from 13.6% to 20.2% (w.b.) did not result in a statistically significant change in discharge rate. However, a further increase to 26.0% (w.b.) led to a significant reduction in flow performance. The relationship between discharge rate and moisture content for the different hopper angles is illustrated in Figure 3, highlighting the overall decreasing trend in flow performance with increasing moisture.

The average discharge rate decreased from $1.066\ kg \cdot s^{-1}$ at 13.6% (w.b.) to $0.823\ kg \cdot s^{-1}$ at 26.0% (w.b.), corresponding to a reduction of approximately 22.8%. This behavior indicates a threshold effect, in which moderate increases in moisture have limited influence on flow, while higher moisture levels lead to a sharp decline in discharge capacity.

This reduction indicates a decrease in flowability at higher moisture levels. The presence of water promotes the formation of capillary bridges between particles, increasing interparticle attractive forces and resistance to flow. As a result, higher moisture levels increase the likelihood of arch formation, ratholing, and unstable flow conditions, even in geometries that would otherwise promote continuous discharge.

These findings are consistent with previous studies reporting that moisture-induced cohesion significantly alters the mechanical behavior of granular agricultural materials, leading to reduced flowability and increased flow instability.

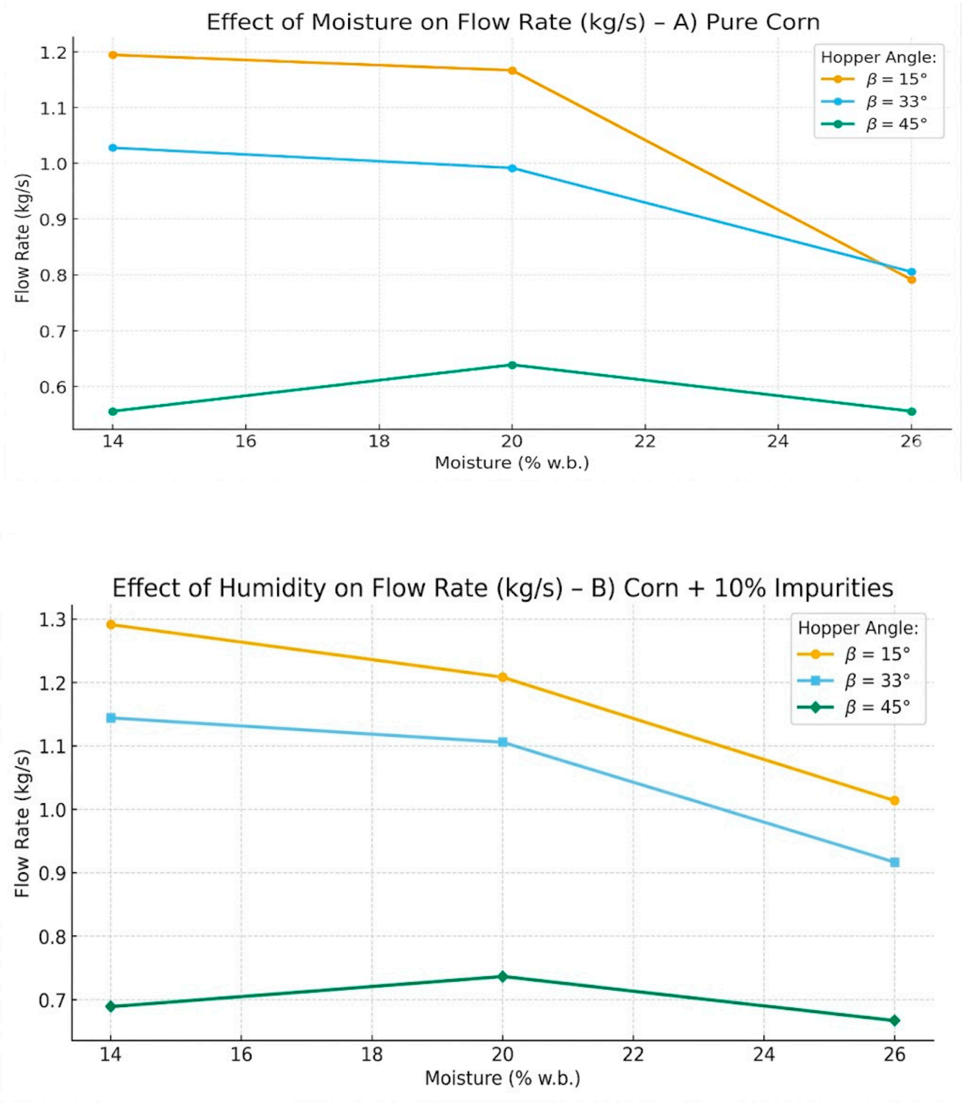

Figure 3. Discharge rate versus moisture content for different hopper angles (15°, 33°, and 45°), with and without impurities.

3.3. Interaction Between Moisture Content and Hopper Geometry

The interaction between moisture content and hopper geometry (U × β) had a significant effect on the mass discharge rate (Table 5), indicating that the influence of hopper angle depends on the moisture level of the maize.

Table 5. Mean discharge rate (kg·s⁻¹) as a function of moisture content and hopper angle.

Moisture (% w.b.)	**β = 15° (kg·s⁻¹)**	**β = 33° (kg·s⁻¹)**	**β = 45° (kg·s⁻¹)**
13.6	1.240	1.134	0.824
20.2	1.185	1.110	0.795

26.0	0.900	0.865	0.683

As shown in Table 5, the effect of hopper angle varied across moisture conditions. At lower moisture levels (13.6% and 20.2% w.b.), the differences between β = 15° and β = 33° were relatively small, while β = 45° consistently resulted in lower discharge rates.

At higher moisture content (26.0% w.b.), the influence of hopper geometry became more pronounced. Under this condition, β = 15° provided the highest discharge rate, whereas β = 45° exhibited a substantial reduction in flow performance. This indicates that steeper hopper configurations are less effective in mitigating the negative effects of moisture-induced cohesion.

The results suggest that, as moisture increases, the role of hopper geometry becomes increasingly critical in controlling flow behavior. Under low-moisture conditions, flow is primarily governed by geometric factors and remains relatively stable across configurations. In contrast, at higher moisture levels, cohesive forces dominate, and the ability of the hopper to promote continuous flow becomes strongly dependent on its inclination.

These findings demonstrate that hopper design should not be defined independently of the expected moisture conditions of the stored material. Instead, geometry and material properties must be considered jointly to ensure reliable discharge performance.

3.4. Effect of Impurities on Discharge Rate

The presence of impurities had a statistically significant effect on the mass discharge rate, as indicated by the ANOVA results (Table 3). As shown in Table 4, the addition of 10% impurities resulted in a higher average discharge rate (1.002 $kg \cdot s^{-1}$) compared to clean maize (0.926 $kg \cdot s^{-1}$). The magnitude of this effect is presented in Table 6.

Table 6. Percentage increase in mass discharge rate with the addition of 10% impurities, as a function of moisture content and hopper angle (β).

	Moisture (% w.b.)		
β°	**13.6%**	**20.2%**	**26.0%**
15°	+8.1%	+4.1%	+29.0%
33°	+12.2%	+11.7%	+13.7%
45°	+24.6%	+13.3%	+13.7%

This result suggests that, within the studied conditions, the inclusion of impurities contributed to an improvement in flowability. A possible explanation for this behavior is the increased granulometric heterogeneity introduced by the presence of smaller particles and fragments, which may enhance particle rearrangement and reduce resistance to flow.

In granular systems composed of particles with different sizes, smaller particles can occupy void spaces between larger grains, potentially reducing interlocking effects and facilitating bulk movement. This effect may partially counterbalance the increase in resistance typically associated with fines in cohesive materials.

It is important to note, however, that this behavior is condition-dependent. Although impurities improved discharge rate in the present study, their presence may also promote segregation and affect other aspects of storage performance, such as aeration efficiency and product quality. Therefore, the beneficial effect observed on discharge rate should not be generalized without considering the broader operational context.

3.5. Segregation Patterns During Discharge

Segregation behavior during discharge was evaluated based on the temporal evolution of the impurity mass fraction (fj) in the collected samples. The results indicate that segregation was strongly influenced by moisture content, with more pronounced effects observed at higher moisture levels, as shown in **Figure 4**.

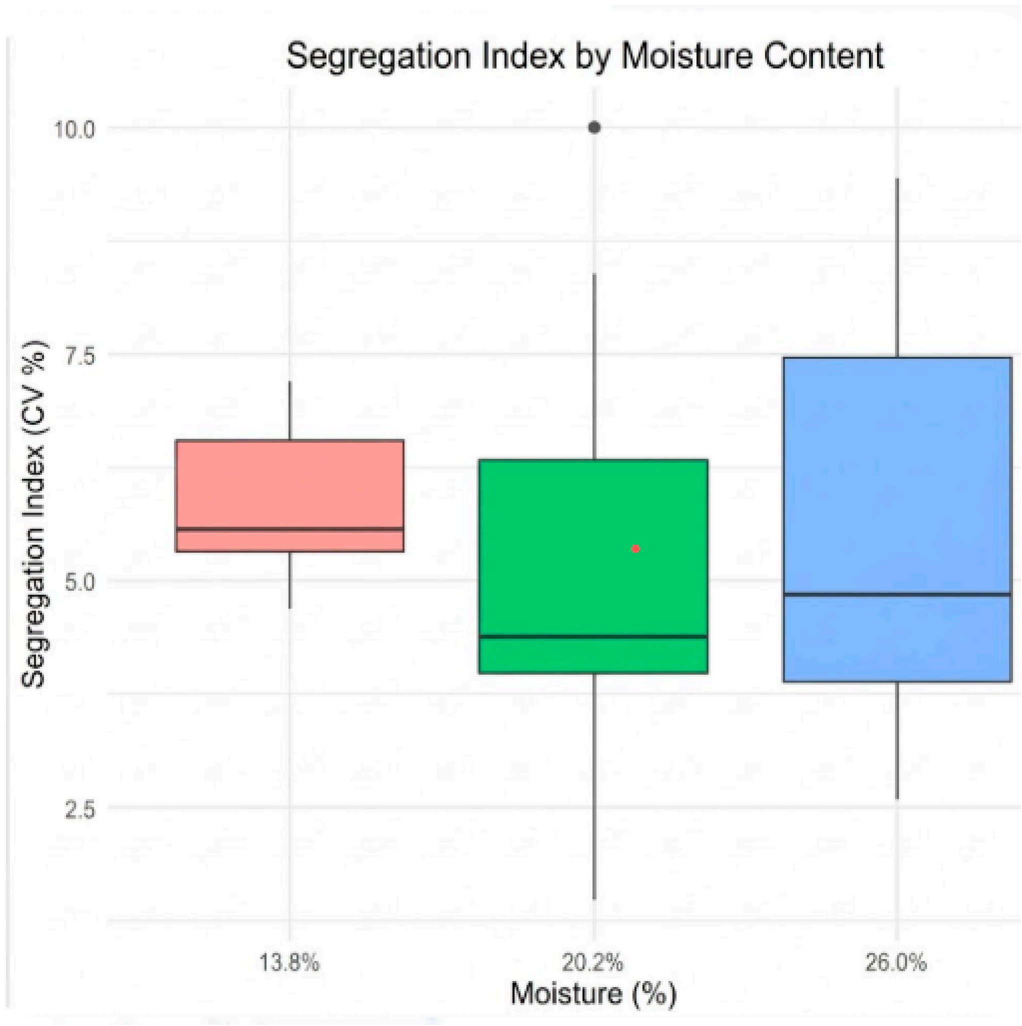

Figure 4. Temporal evolution of impurity fraction (%) during discharge, based on five sequential samples, for moisture contents of 13.6% and 26.0% (w.b.) in the β = 15° silo.

At lower moisture contents (13.6% and 20.2% w.b.), the impurity fraction remained relatively stable throughout the discharge process, indicating limited segregation. In contrast, at 26.0% (w.b.), a progressive increase in impurity concentration was observed toward the final stages of discharge, suggesting the occurrence of segregation along the vertical axis of the silo.

This behavior is consistent with classical segregation mechanisms in granular materials, particularly percolation and trajectory segregation. During discharge, smaller particles and fragments tend to migrate through the interstices between larger grains, accumulating preferentially in specific regions of the bulk material. As discharge progresses, these regions are mobilized, leading to variations in impurity concentration over time.

The intensification of segregation at higher moisture levels may be related to the combined effects of increased cohesion and reduced flow uniformity. Under these conditions, the formation of preferential flow channels can enhance particle separation, resulting in more heterogeneous discharge patterns.

These findings indicate that moisture not only affects flowability but also plays a key role in segregation dynamics, which may have implications for product quality and storage management.

3.6. Slip–Stick Behavior

An intermittent flow behavior, identified as Slip–stick , was observed under a specific experimental condition: β = 15°, moisture content of 26.0% (w.b.), and the presence of 10% impurities. This phenomenon was not observed in any other experimental condition, indicating a critical flow situation.

Video analysis (Figure 5) revealed a distinct sequence of events during discharge. As shown in Figure 5a, an initial stagnation phase (stick) was observed, lasting approximately 30 seconds, during which little or no material flowed and the top surface of the granular bed remained nearly unchanged.

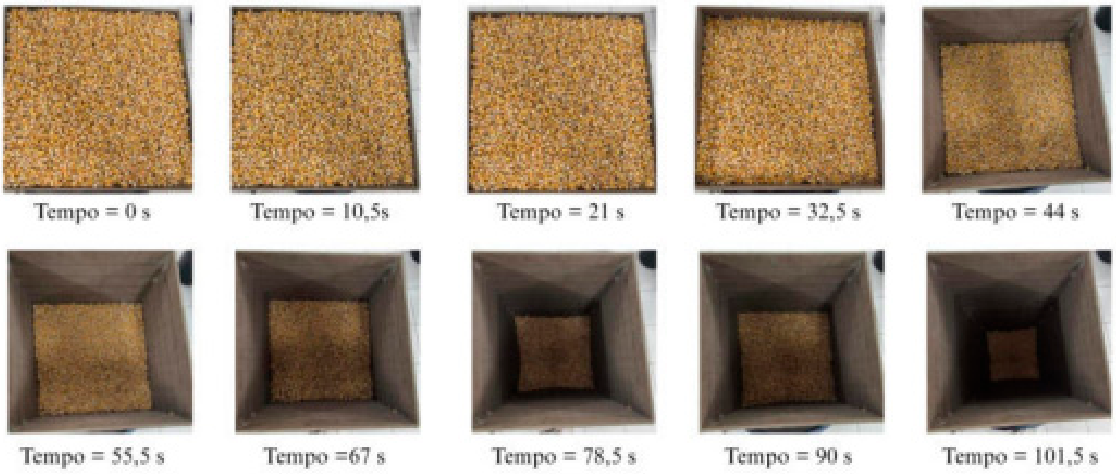

Figure 5. Sequence of images illustrating the Slip–stick phenomenon in the β = 15° silo at 26.0% moisture content (w.b.) with 10% impurities: (a) stagnation phase (0–30 s); (b) rupture with vibration (32.5 s); (c) established funnel flow (after 32.5 s).

This phase was followed by a sudden rupture event (slip) at approximately 32.5 seconds (Figure 5b), characterized by rapid material discharge accompanied by noticeable vibration and audible noise. After this event, the flow stabilized (Figure 5c) and continued until complete emptying, predominantly in a funnel flow pattern.

The total discharge time for this test was 101 seconds, with a total discharged mass of 74.8 kg, resulting in an average discharge rate of 0.74 kg·s^{-1}.

For comparison, under equivalent conditions without the occurrence of Slip–stick (β = 15°, 26.0% w.b., with 10% impurities), the average discharge rate was 0.89 kg·s^{-1}, based on an average discharge time of 84.5 seconds for a total mass of 79.13 kg.

The occurrence of Slip–stick resulted in a reduction of approximately 23.0% in the average discharge rate relative to the stable condition. In addition, the phenomenon was associated with noticeable structural vibration and an irregular discharge pattern.

Post-event observations indicated that, after the rupture, the granular bed developed a preferential flow channel that persisted until the end of the discharge process.

4. Discussion

The results of this study demonstrate that maize flow in prismatic silos is governed by a complex interaction between material properties (moisture content and impurity presence) and hopper geometry (angle β) [15]. The integrated analysis of these factors proposed in this work reveals behaviors that would not be identified in studies addressing each variable in isolation, thereby confirming the need for a structured experimental approach such as the one adopted here.

4.1. Moisture as a Critical Factor and Flow Regime Transition

The results demonstrate that moisture content is the dominant factor controlling the discharge behavior of maize in prismatic silos. The reduction in discharge rate with increasing moisture is consistent with the theory of capillary-induced cohesion in granular materials described by Schulze [3] and Nedderman [4]. As moisture increases, liquid bridges form between particles, enhancing apparent cohesion and increasing resistance to flow

This behavior agrees with previous studies on maize-based materials. Chinwan et al. [11] reported a progressive reduction in flowability with increasing moisture, accompanied by higher angles of repose, while Moya-Ignacio et al. [10] observed increases in apparent cohesion and changes in internal friction in rewetted maize grains. These findings confirm the strong dependence of mechanical behavior on moisture content.

From the perspective of Jenike's theory [2], the increase in cohesion shifts the operating condition of the silo toward regions associated with difficult flow or even no-flow. As a result, the critical outlet size increases and the likelihood of arching and ratholing becomes higher, even for geometries that would otherwise ensure satisfactory discharge. This explains the reduction in discharge rate observed at 26.0% (w.b.) across all hopper configurations.

The regression equation

$$Q = 1.506 - 0.0272 \cdot U; \ (R^2 = 0.87) \qquad (7)$$

provides a quantitative description of this trend, indicating an average reduction of approximately 2.7% in discharge rate per percentage point increase in moisture above 20% (w.b.).

The significant interaction between moisture content and hopper angle (U × β) highlights an important design implication: hopper geometry should be defined according to the expected moisture range of the stored material. This behavior is consistent with flow regime maps proposed for planar silos [6] and with design criteria such as EN 1991-4, which associate lower hopper angles with a greater tendency toward mass flow and reduced stagnant zones, as reported by Gandia et al. [5].

4.2. Discharge Rate and Impurity Content

The consistent increase in discharge rate with the addition of 10% impurities across all experimental conditions represents one of the most relevant findings of this study. The observed increments, reaching up to 29.0% under high-moisture conditions (26.0% w.b. and β = 15°), challenge the conventional assumption that impurities are always detrimental to flow behavior.

Traditional grain storage practices, as recommended in technical manuals such as those from EMBRAPA [12] and industry guidelines [13], emphasize rigorous pre-cleaning to ensure product quality during storage. While this approach is essential from a preservation standpoint, the present results indicate that, from a strictly mechanical perspective, a moderate fraction of fine particles may enhance flowability under cohesive conditions.

This effect can be attributed to changes in the internal structure of the granular bed. The presence of fine particles increases granulometric heterogeneity, modifying interparticle contacts and reducing resistance to movement. Fine particles may occupy void spaces between larger grains, reducing interlocking effects and facilitating particle rearrangement during discharge. Additionally, under high-moisture conditions, the introduction of particles of different sizes may disrupt the formation of continuous capillary bridges, weakening the cohesive network and promoting flow. These mechanisms are consistent with observations reported by Jian [9] and with classical concepts of granular flow behavior [3,4].

It is important to emphasize that this beneficial effect was observed for a specific impurity fraction (10%) and for fines derived from maize itself. Higher impurity contents or different particle characteristics may lead to distinct outcomes. Therefore, the relationship between impurity content and discharge performance is likely non-linear, with the existence of an optimal range beyond which negative effects, such as excessive segregation or operational issues, may outweigh the mechanical benefits.

4.3. Progressive Segregation in Cohesive Systems

The segregation patterns observed in this study differ significantly from those classically reported for dry, non-cohesive materials. Jian, Narendran, and Jayas [8] and Jian [9] extensively documented sifting segregation mechanisms during silo filling with central feeding, in which fine particles tend to concentrate in the central region while larger particles migrate toward the periphery. This type of segregation occurs predominantly during the filling stage, prior to discharge.

In contrast, the present results showed a progressive segregation pattern during discharge under high-moisture conditions (26.0% w.b.), characterized by a continuous increase in impurity fraction in the collected samples. This behavior indicates a mechanism distinct from classical sifting during filling, suggesting a dynamic segregation process associated with the flow itself.

A plausible explanation involves the flow dynamics under conditions approaching funnel flow. At high cohesion levels, flow tends to concentrate in a central channel, with reduced particle mobility in the surrounding regions. Fine particles, due to their lower inertia and reduced confinement, are preferentially mobilized within this central flow channel and discharged earlier. As discharge progresses, the proportion of fines in the remaining material increases, resulting in the progressive segregation observed.

Gray and Ancey [15], in their work on multi-scale segregation in granular flows, describe kinematic segregation mechanisms that may explain this behavior. Experimental studies have confirmed that funnel flow regimes promote more pronounced segregation compared to mass flow [18].

In dense and cohesive flows, segregation can arise from differences in particle mobility under velocity and stress gradients, leading to the preferential concentration of fines in specific flow regions. This dynamic segregation during discharge has also been observed in granular systems during hopper discharge, particularly in studies combining experimental and discrete element methods [19].

This phenomenon has important practical implications for silo operation. In partial discharge scenarios involving moist maize with impurities, the material withdrawn at later stages may present a significantly higher fines content compared to the initial discharge, compromising batch homogeneity. This variation may affect downstream processes such as drying, milling, and commercialization, and should therefore be considered in operational planning.

4.4. Implications of Stick-Slip Behavior

The occurrence of stick-slip behavior under the most critical condition of this study (β = 15°, 26.0% w.b., 10% impurities) experimentally validates theoretical predictions of intermittent flow regimes in cohesive materials. Schulze [3] and Zhou and Ooi [16] describe stick-slip as resulting from the successive formation and collapse of cohesive arches above the outlet, a behavior expected when cohesion is sufficient to form stable structures but not high enough to permanently block flow. Theoretical models further explain this behavior through the formation and collapse of cohesive arches in the granular bed [20].

The sequence observed in this study—initial low flow during the first 30 seconds (arch formation), followed by abrupt rupture with intense vibration (collapse), and subsequent establishment of continuous funnel flow—closely matches the pattern reported in the literature [6,14]. The observed vibration during rupture is a key indicator of dynamic loads that may be transmitted to the silo structure.

The operational impact of stick-slip behavior is significant and multifaceted. First, the reduction of approximately 23.0% in discharge rate compared to the equivalent stable condition demonstrates that intermittent flow substantially compromises discharge efficiency, potentially affecting process scheduling and material handling operations.

Second, the intense vibration observed during arch collapse (at approximately 32.5 s) may generate dynamic loads that exceed static design loads. According to Jenike [2], such conditions can lead to structural fatigue or failure, particularly in inadequately designed or deteriorated silos.

Third, the intermittent nature of stick-slip reduces the reliability of systems that depend on steady flow, such as feeders, continuous dryers, and pneumatic conveying systems, where flow stability is essential for process control.

Finally, the establishment of funnel flow after arch collapse indicates that stick-slip may permanently alter the internal flow configuration of the granular bed, with implications for subsequent discharge behavior even under similar loading conditions.

The occurrence of this phenomenon exclusively under the most critical condition suggests the existence of a “risk zone” in which stick-slip behavior may arise. The experimental identification of this condition represents an important contribution of this study to the safe design and operation of silos.

4.5. Limitations and Future Work

The results of this study should be interpreted considering some inherent limitations.

First, the experiments were conducted using reduced-scale silos (0.07–0.10 m^3), which allowed precise control and detailed observation of flow phenomena, but do not permit direct extrapolation of absolute discharge rates to full-scale systems. Nevertheless, the observed mechanisms and trends, such as the interaction between moisture content and hopper geometry, and the effect of impurities, are expected to remain valid at larger scales, although their magnitude may vary.

Second, the silo walls were constructed from MDF, whose frictional properties differ from those of galvanized steel commonly used in industrial silos. This difference may have influenced flow patterns, and future studies should evaluate the effect of wall material using surfaces with different roughness and finishes.

Third, the investigated moisture range (13.6%–26.0% w.b.) covers critical flow conditions but does not include extremely high moisture levels (>30% w.b.) or very dry conditions (<12% w.b.), both of which may lead to distinct flow behaviors.

Fourth, a fixed impurity fraction (10%) was adopted, representative of uncleaned grain. Future studies should explore different impurity levels and compositions to establish a more comprehensive relationship between impurity content and discharge performance.

Finally, the experimental dataset provides a valuable basis for the validation of numerical models, particularly discrete element method (DEM) simulations, which could extend the analysis to a broader range of geometries and material properties. In addition, more advanced segregation metrics, such as the Lacey mixing index [16] and normalized absolute deviation approaches [9], could be applied to improve the quantitative characterization of segregation patterns.

5. Conclusions

This study experimentally evaluated the combined effects of moisture content, hopper geometry, and impurity presence on the flow behavior, segregation, and discharge rate of maize in reduced-scale silos. The factorial design (3 × 3 × 2) enabled the identification of significant interactions between variables, highlighting the importance of an integrated approach to silo operation and design.

Moisture content was identified as the dominant factor controlling flow behavior. Increasing moisture to 26.0% (w.b.) significantly reduced discharge rate, indicating that cohesion induced by capillary forces governs flow resistance under these conditions. The linear relationship obtained between discharge rate and moisture content provides a practical reference for estimating flow performance under operational conditions.

A significant interaction between moisture content and hopper angle ($U \times \beta$) demonstrated that there is no universally optimal geometry. While intermediate angles performed adequately under lower moisture conditions, steeper hoppers (lower β) were more effective in maintaining flow under high-moisture conditions, whereas β = 45° showed consistently poor performance.

The addition of 10% impurities increased discharge rate under all tested conditions, with more pronounced effects at high moisture levels. This result suggests that particle size heterogeneity may enhance flowability under cohesive conditions, indicating that the effect of impurities on flow is not strictly detrimental and depends on the interaction between material properties and flow regime.

Segregation behavior differed from classical patterns observed in dry materials. Under high moisture conditions, a progressive increase in impurity concentration during discharge was observed, indicating a dynamic segregation mechanism associated with flow. This behavior has important implications for product homogeneity, particularly in partial discharge operations.

stick-slip behavior was identified under critical conditions (high moisture, low β, and presence of impurities), resulting in intermittent flow, vibration, and a reduction of approximately 23% in discharge rate. This phenomenon represents a significant operational risk, affecting flow predictability, structural loading, and process reliability.

Overall, the results demonstrate that efficient silo operation requires the integrated consideration of moisture content, hopper geometry, and impurity management. The findings provide practical guidance for improving discharge performance while highlighting potential trade-offs between flow efficiency and product quality.

Author Contributions: Conceptualization, R.M.G. and W.M.R.; methodology, R.M.G. and D.M.F.; validation, R.M.G.; formal analysis, R.M.G.; investigation, W.M.R. and D.M.F.; data curation, W.M.R.; writing—original draft preparation, R.M.G.; writing—review and editing, R.M.G., D.J.C.A. and F.C.G.; supervision, R.M.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors would like to thank the Federal University of Lavras (UFLA) and the Agricultural Products Processing Research Center (CPPPA) for providing the infrastructure and materials used in this study. During the preparation of this manuscript, the authors used ChatGPT (OpenAI, GPT-5.3) for language refinement and text editing. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflict of interest.

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