

Modeling the coefficient of friction on various surfaces using multiple linear regressions

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Abstract: When analyzing and designing equipment for post-harvest handling, food processing, and storage, it is crucial to understand the coefficient of friction of legume crops on different structural surfaces. The article examines the effects of various treatments on the static friction coefficient and dynamic friction coefficient of *Phaseolus vulgaris* L. Statistical analytic techniques were used to determine the significance of the single effect, dual interaction effect, and triple interaction effect of treatments (moisture content, contact surface, and sliding velocity) on static and dynamic friction coefficients, respectively. The static and dynamic friction coefficients on various contact surfaces were predicted using multiple linear regression modeling. Mean relative deviation modulus, root mean square error, and coefficient of determination (R^2) were three statistical measures used to assess the predictive power of constructed multiple linear regression models. The significant increases in moisture content and contact surface single effect were slightly smaller than the significant increases in dual interaction effect of treatments on static friction coefficient, which were found to be 3.2 and 3 times the former, respectively. With regard to the dynamic, the treatments' significant increases in the triple interaction effect were 8.8, 3.7, and 8.9 times larger than the corresponding single effects for sliding velocity, moisture content, and contact surface. The single effect of the contact surface on the dynamic was similarly found to be 2.4 times greater than that of sliding velocity or moisture content, while the single effect of the contact surface on the static was found to be 1.1 times greater than that of moisture content. Static and dynamic could be precisely predicted by proposed multiple linear regression models, based on a reasonable average of statistical parameters, which were $R^2 = 0.941$, RMSE = 0.02281, and MRDM = 3.151% for static friction coefficients and $R^2 = 0.968$, RMSE = 0.01295, and MRDM = 2.153% for dynamic friction coefficients. Using the models for direct prediction of static and dynamic friction coefficients, corresponding to each contact surface, based on sliding velocity and moisture content is suggested in practice.

Keywords: contact surface, dynamic friction coefficients, phaseolus vulgaris, static friction coefficients, treatment effects

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1 Introduction

The common bean is one of the primary

worldwide sources of edible legumes (*Phaseolus vulgaris* L.). The leading producers are the India,

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Brazil, Myanmar, the United States, China, and Mexico (FAO, 2020). In 2021, dry beans produced on 28 million hectares worldwide yielded over 20 million tons. Grain-based legumes are essential for nourishment for humans (Degirmencioglu et al., 2019), particularly for low-income people in underdeveloped countries (Fernando, 2021). Compared to grains, their protein content is almost 2-3 times higher (Wodajo et al., 2021), they are composed of a substantial amount of protein and are often referred to as "poor man's meat." For a sizable segment of the global populace, mostly in developing nations, they also provide an affordable and significant source of starch, dietary fiber, and protein (FAO, 2020).

According to Amsalu et al. (2018), Ethiopia has been producing and exporting common beans for more than 50 years. The country produces red, white, black, and mottled varieties of common beans (Abera et al., 2020). The most widely available commercial kinds are pure red and white beans; as market demand increases, they are also being grown more frequently (Tekalign et al., 2022). Due to the increased demand for these commodities in the local and international markets, in recent years, there has been a discernible increase in nationwide production area and volume (Kefelegn et al., 2020). This illustrates how inefficient postharvest handling, primarily done by hand, persists in Ethiopia, considering the country's significant worldwide yield of common beans (Befikadu, 2018).

To build appropriate systems, equipment, and infrastructures for interacting with, cultivating, gathering, and agriculture-related processing, comprehension of the engineering characteristics of agricultural products is essential. Bayano-Tejero et al. (2023) state that when designing, cleaning, sizing, and grading machines, the three main dimensions of length, breadth, and thickness must be considered (Samrawit, 2023). Aspect ratio (Omobuwajo et al., 1999), projected area (Mirzabe et al., 2013), roundness (Baryeh, 2002), sphericity and surface area

(Mohsenin, 1986; Baryeh, 2002), arithmetic mean diameter and geometric mean diameter (Baryeh, 2002; Mpotokwane et al., 2008), and Mohsenin (1986) computation of seeds' volume (V) were among the measurements taken.

When developing the seed metering mechanism of seed drills (Zewdie et al., 2024a; Önal and Ertuğrul, 2011), as well as transportation, sorting and sizing systems, bean seed size is a critical parameter (Nciri et al., 2014); Larger-seeded bean varieties absorb water more slowly and take longer to cook than smaller-seeded varieties (Sahin and Sumnu, 2006). During soaking, seed size affects electrical conductivity tests (Chhabra and Kaur, 2017).

Surface area plays a crucial role in heat and mass transfer processes such as drying and various thermal applications. An agricultural product's surface area usually indicates how it will behave in a flowing fluid and how easy it will be to remove unwanted contaminants from the product while cleaning it with a pneumatic tool (Omobuwajo et al., 1999). The surface area helps determine the agricultural products quality and quantity, color, respiration data, and aerodynamic calculations (Singh and Heldman, 2009).

The physical parameters alter the rate of moisture transfer and heat transfer in the approach, which makes them crucial properties in drying and ventilation processes. The bulk density determines the conveyor capacity and amount of produce storage needed. When separating materials, the actual density is taken into account. Grain hopper and storage equipment sizing is determined by porosity (Kakade et al., 2019). The engineering characteristics of agricultural materials are influenced by the moisture content, a physical parameter (Zewdie et al., 2024b; Sahin and Sumnu, 2006; Bhise et al., 2014; Degirmencioglu and Srivastava, 1996; Singh and Heldman, 2009). Equipment design that is effective, affordable, and efficient depends on having a comprehension of the traits of agricultural materials at varying moisture levels (Chhabra and Kaur, 2017; Bhise et al., 2014). When constructing storage and

solid flow mechanisms (Emrani and Berrada, 2023) and material handling equipment (Pawar et al., 2023), another essential consideration to take into account is the coefficient of resistance (Bako and Aguda, 2023). An essential factor in predicting pressure from seeds on walls (Amin et al., 2004) is the coefficient of friction (Bhise et al., 2014) between the seed and the wall.

On various contact surfaces, legumes have varying friction coefficients. Thus, precise measurement of the crop's friction coefficients on various contact surfaces can help optimize the operation of mechanical equipment (conveyors, separation, cleaning, drying, and storing tools), which will reduce harmful damages and increase economic efficiency, respectively (Mohsenin, 1986).

When there are two contact surfaces, friction forces are generated. Static friction force is needed to move an object while it is initially stationary, and dynamic friction force is needed to move an object continuously at a certain speed. The static and dynamic friction forces are represented by the static friction coefficient and dynamic friction coefficient, respectively. The moisture content of a crop affects its static friction coefficient and dynamic friction coefficient. The sliding velocity is moreover a significant element in the case of dynamic friction coefficient (Mohsenin, 1986). In haricot bean grain handling machinery and storage structures, frictional forces are generated on a vertical plane. Frictional forces are significant in the discharging process in the plug flow region on the walls and bottom of storage bins.

The interaction between haricot bean particles and the bin wall's surface affects the static friction coefficient and dynamic friction coefficient, and subsequently the frictional forces (Thompson et al., 1988). The distribution and magnitude of loads placed on storage structures are greatly impacted by this interaction (Zhang et al., 1988). However, there is still a lack of information regarding how various treatments affect the static friction coefficient and dynamic friction coefficient. Thus, more research is

required to precisely understand how the haricot bean legume crop behaves in terms of friction on various contact surfaces.

An analysis of published works revealed that while the static friction coefficient of legume crops has been examined by a number of earlier researchers (Deo et al., 2023), and Saparita et al. (2019), no comprehensive study has been conducted to ascertain the impact of moisture content and contact surface on the static friction coefficient of haricot beans. Perfect attempts to report the effects of moisture content, contact surface, or sliding velocity on the dry matter content (dynamic friction coefficient) of haricot beans are not readily available in the literature Baryeh (2002), and Mohsenin (1986). Thus, a thorough analysis of static friction coefficient and dynamic friction coefficient for haricot beans that takes into account a number of experimental situations may be helpful for optimizing structures used for processing and storage, particularly crop bins for legumes.

Hence, agricultural products have inherent variability in their engineering parameters, including moisture contents, size, shape, surface area, sphericity, density, porosity, volume of seed, coefficient (both static & dynamic), and angle of repose (Jahanbakhshi, 2018; Ertuğrul et al., 2022; Zewdie et al., 2024a). This variability poses challenges in designing, modification, improvement, or development of machines efficiently and effectively. A lack of thorough data, inconsistent testing procedures, and a poor comprehension of the relationship between the agricultural product and the machine are a few additional challenges (Elijah et al., 2018). The aim of this manuscript is to find out how the frictional characteristics (both static & dynamic) coefficients of common beans (*Phaseolus vulgaris* L.) influence the design of a thresher for a particular bean variety. This will help to establish the convenient reference data required to develop equipment for handling, cleaning, storing, transportation, drying, and other processes involving the seed.

2 Materials and methods

Awash Melkassa Research Center, Oromia regional State, Ethiopia, provided nine improved varieties of common beans that grow in several regions of the country: KAT-B1, KAT-B9, SCR-15, Deme, Belete, Tafach, Ado, Awash Tikur, and BZ-2 (Figure 1). For further investigation, the sample seeds were manually picked and cleaned of foreign elements such as dust, stones, dirt, immature seeds, damaged seeds, and other contaminants. To enable homogeneous absorption of water into grains, the hydrated samples were packed in separate polyethylene bags and refrigerated for ten days at $5^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ (Nimkar et al., 2005). Nearly two hours before each frictional experiment began; the necessary number of samples was placed in an ambient environment to warm up to room temperature (Abalone et al., 2004).

Physical properties: The dimensions of one thousand randomly chosen bean seeds of each variety were determined. Using an electronic vernier caliper with a precision of 0.01 mm, the three fundamental axial dimensions of *Phaseolus vulgaris* were measured. *Phaseolus vulgaris* mean diameters were computed as geometric mean (D_g), arithmetic mean (D_a), square mean (D_s), and equivalent mean (D_e) were determined using Equations 1-4 (Fraser et al., 1978; Mohsenin, 1986; Baryeh, 2002; Haciseferoğulları et al., 2003; Altuntaş and Yıldız,

2007; Sundaram et al., 2014; Zewdie et al., 2024b).

$$D_g = \sqrt[3]{L \times W \times T} \quad (1)$$

Where,

D_g is geometric Mean Diameter, mm.

$$D_a = (L+W+T)/3 \quad (2)$$

Where,

D_a is arithmetic Mean Diameter, mm .

$$D_{sq} = \sqrt{LW + WT + TL} \quad (3)$$

Where,

D_{sq} is square Mean Diameter, mm.

$$D_{eq} = \left[\frac{L(W+T)^2}{4} \right]^{\frac{1}{3}} \quad (4)$$

Where,

D_{eq} is equivalent Mean Diameter, mm.

Experimental design and data analysis: A randomized complete block factorial design was employed in the tests to investigate the impact of varying structural surfaces and moisture content on the coefficient of friction (Zewdie et al., 2024a). The levels of one factor were formed by the moisture levels, and the levels of the other factor were formed by the structural surfaces. Each experimental cell for the two factors contained four and five observations, respectively. For every type of grain, there were a total of 100 observations. Regression analysis was used to produce empirical predictive equations and Analysis of Variance (ANOVA) was used to identify treatment effects on the collected data.



KAT B1



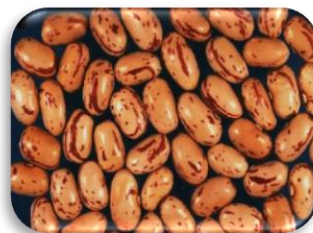
KAT B9



SCR 15



Deme



Tafach



BZ-2

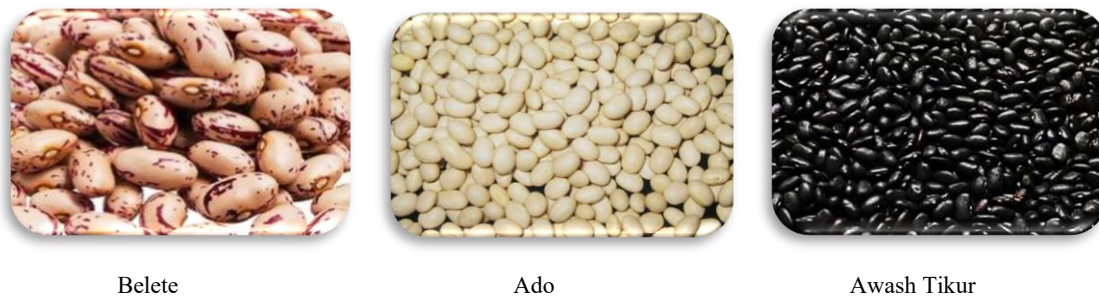


Figure 1 Awash Melkassa Research Center's national common bean research programs improved varieties

Frictional experiments: Utilizing a static coefficient of friction measurement device, the samples' static coefficient of friction was accurately determined at various moisture content levels on five contact surfaces: rubber, glass, aluminum, galvanized steel, and plywood. The device was first proposed by Singh and Goswami (1996), and Lorestani (2012) and Shafaei and Kamgar (2017) made mechanical and electrical improvements (Zewdie et al., 2024a). Figure 2a provides a detailed schematic of the instrument. Available in the literature are the instrument's technical specs and engineering details. With the use of a DFC measuring device, the DFC of the samples was also precisely determined on each kind of contact surface at various moisture content

levels and sliding velocities (1, 3.5, 5.75, 9.25, and 12.5 cm s^{-1}). To protect the samples from potential harm, the greater sliding velocities were disregarded. Clark and McFarland (1973) made the initial suggestion for the instrument, which was later refined and widely utilized by Thompson et al. (1988). Figure 2b shows a schematic illustration of the apparatus. The literature provides a thorough explanation of the instrument's engineering considerations and development information. Each experiment began with the contact surface being thoroughly cleaned with compressed air to remove any residue from earlier tests. At a constant normal pressure of 22.5 kPa, each experiment was completed in five replications.

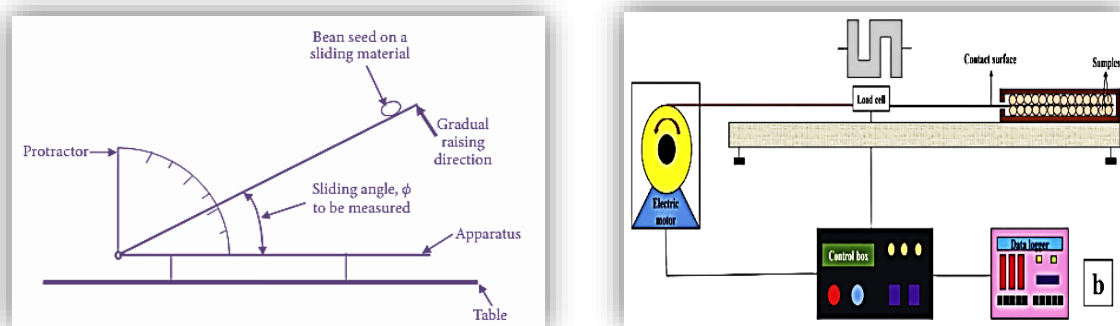


Figure 2 Schematic of the used SFC (a) and DFC (b) measuring instrument

Statistical analysis: Data on sliding velocity (five levels), moisture content (five levels), and contact surface (five types) were examined in 125 and 625 sets for Static and dynamic friction coefficient, respectively. Each analysis was conducted with five replications. The effects of sliding velocity, contact surface, moisture content, and their dual interaction effect and triple interaction effect on dynamic friction coefficient were also examined, as was the impact of moisture content, contact surface, and their dual

interaction effect on Static friction coefficient using the ANOVA approach. Using DMRT at 1% significance level, differences in the treatment means were also compared.

Development of multiple linear regression models: Using SPSS 21 software (SPSS Inc., Chicago, IL, USA), the Multiple linear regression models, based on Equation 5, were generated for the means of data (25 and 125 sets for Static and dynamic friction coefficient, respectively) collected from the

five-replication experiments. For each contact surface, the model was fed one input variable (moisture content) and two input variables (slide velocity and moisture content), respectively, to predict Static and dynamic friction coefficient. At the 99% probability level, the derived models' constants and coefficients were likewise found to be significant.

$$FC = a_0 + a_1x_1 + a_2x_2 + \dots + a_nx_n + \varepsilon \tag{5}$$

$$Skewness = \frac{n}{(n-1)(n-2)} \sum_{i=1}^n \left(\frac{x_i - x_{avg}}{STDEV} \right)^3 \tag{6}$$

$$kurtosis = \left\{ \frac{n(n-1)}{(n-1)(n-2)(n-3)} \sum_{i=1}^n \left(\frac{x_i - x_{avg}}{STDEV} \right)^4 \right\} - \frac{3(n-1)^2}{(n-2)(n-3)} \tag{7}$$

$$R^2 = \frac{\sum_{i=1}^N (FC_{act,i} - FC_{actave}) - \sum_{i=1}^N (FC_{act,i} - FC_{mod,i})}{\sum_{i=1}^N (FC_{act,i} - FC_{actave})} \tag{8}$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (FC_{mod,i} - FC_{act,i})^2} \tag{9}$$

$$MRDM = \frac{100}{N} \sum_{i=1}^N \left(\frac{|FC_{mod,i} - FC_{act,i}|}{FC_{act,i}} \right) \tag{10}$$

Coefficient of determination (R^2), Root mean square error (RMSE), Mean relative deviation modulus (MRDM), Skewness, and kurtosis were statistical indices that were computed between the modeled and actual Static and dynamic friction coefficient using the following equations in order to evaluate the predictive power of the constructed models.

3 Results and discussion

Statistical descriptions: The range of the standard deviations of static and dynamic friction coefficient for every set of replications was found to be 0.004 - 0.019 and 0.003 - 0.029, respectively. The measuring instruments' exceptional precision and stability were confirmed by the limited range of standard deviations. Table 1 provides statistical descriptor parameters for the measured static and

dynamic friction coefficient of haricot beans, which correspond to five degrees of moisture content and sliding velocity on various contact surfaces. Glass and rubber had the lowest and greatest levels of moisture content, respectively, where the minimum and maximum Static friction coefficient were found, as shown in Table 1. It was inferred by the static friction coefficient improper coefficient of variation and coefficient of non-uniformity that the Static friction coefficient changed dramatically when the type of contact surface or moisture content was altered. The minimum and maximum amounts of moisture content and sliding velocity on glass and rubber, respectively, were found to have the lowest and highest dynamic friction coefficient, similar to Static friction coefficient.

The contact surface type, sliding velocity, and moisture content variations all had a significant impact on the dynamic friction coefficient, as seen by the improper coefficient of variation and coefficient of non-uniformity for the dynamic friction coefficient. When the coefficient of variation and coefficient of non-uniformity for the static and dynamic friction coefficient were compared in Table 1, it became clear that the dynamic friction coefficient related values were greater than the static friction coefficient related ones. Two treatments were used to investigate static friction coefficient behavior, while three treatments were used in the case of dynamic friction coefficient. As a result, dynamic friction coefficient had greater fluctuations than static friction coefficient, which led to higher dynamic friction coefficient related values.

Statistical analysis: The ANOVA results for static and dynamic friction coefficient of haricot beans under various treatments are shown in Tables 2 and 3, respectively.

Table 1 Statistical analysis of the common beans measured static and dynamic friction coefficients

Type coefficient	Mean	Standard deviation	Minimum	Maximum	CV (%)	CNU (%)
Static Friction Coefficient	0.512	0.121	0.240	0.693	23.63	88.48
Dynamic Friction Coefficient	0.467	0.124	0.204	0.809	26.55	129.55

Table 2 ANOVA findings for haricot bean static friction coefficient

Source of variation	Degree of freedom	Sum of squares	Mean square	F value
Moisture Content (MC)	4	0.771	0.193	1327.275**
Contact Surface (CS)	4	1.037	0.259	1786.704**
MC x CS	16	0.036	0.002	15.660**
Error	100	0.015	0.00015	
Total	124	1.859		

Note: ** Significant at $P < 0.01$.

Tables support the statement that, at the 1% probability level ($P < 0.01$), the effects of the treatments and their combinations (dual interaction effect and triple interaction effect) on static and dynamic friction coefficient were statistically

significant. To create the best operating conditions, engineers must consider these effects on the static and dynamic friction coefficients while designing crop handling equipment and storage structures.

Table 3 Results of the ANOVA for the haricot bean's dynamic friction coefficient

Source of variation	Degree of freedom	Sum of squares	Mean square	F value
Moisture Content (MC)	4	1.418	0.355	1406.704**
Contact Surface (CS)	4	6.461	1.615	6408.071**
Sliding velocity (SV)	4	1.362	0.341	1351.311**
MC x CS	16	0.182	0.011	45.023**
MC x SV	16	0.015	0.001	3.639**
CV x SV	16	0.085	0.005	21.169**
MC x CS x SV	64	0.033	0.001	2.053**
Error	500	0.126	0.000252	
Total	624	9.682		

Effect of treatments - single effect

Moisture content - The effects of moisture content on the static and dynamic friction coefficients of haricot beans as determined by Duncan's Multiple Range Test are presented in Table 4. The Table suggested that an increase in moisture content from 9.4% to 13.5% (db) resulted in a rise in static and dynamic friction coefficients of 59% and 33.75%, respectively. The cohesive force between the beans and the contact surface increases as the moisture content rises because the beans get stickier. Static friction coefficients (Konak et al., 2002) and dynamic friction coefficients (Kalkan and Kara, 2011) will rise as a result of stronger cohesive forces.

Sliding velocity: Based on descending sliding velocity and increasing dynamic friction coefficients of haricot beans, Table 4 presents the Duncan's Multiple Range Test results. The Table values indicate that a significant shift in dynamic friction coefficients from the lowest to highest value of 33.5% resulted from a sliding velocity increment of 1 to 12.5

cm s⁻¹. It is possible that the dynamic friction coefficients growth was caused by stronger adhesive force at higher sliding velocities (Thompson et al., 1988).

Contact surface: The contact surface had a substantial impact on the static and dynamic friction coefficients of haricot beans, as shown by the Duncan's Multiple Range Test results (Table 4). On the contact surfaces of aluminum and glass, respectively, the lowest static and dynamic friction coefficients were observed. The difference between the lowest and greatest values of the static and dynamic friction coefficients was 64% and 80.29%, respectively. The reason for this was the variation in contact surface roughness and smoothness. A smoother surface reduced the adhesion force between the samples and the surface, which in turn reduced the static and dynamic friction coefficients. The friction coefficients on the contact surfaces of aluminum and galvanized steel were predicted to be comparable; however the results did not support this

hypothesis. Compared to galvanized steel, aluminum sheet may have a smoother, more polished surface. The static coefficient of friction varied between 0.276 and 0.386 on the surface of iron sheets, 0.294 to 0.435 on stainless steel, 0.317 to 0.434 on galvanized iron, 0.321 to 0.451 on medium density fiberboard, 0.319 to 0.480 on aluminum, 0.310 to 0.470 on

painted sheets, 0.320 to 0.440 on glass, 0.333 to 0.447 on plastic, and 0.374 to 0.575 on rubber (Zewdie et al., 2024b). Perforated sheet surfaces showed the highest static coefficients of friction, followed by rubber, plastic, plywood, glass, aluminum, galvanized iron, painted sheet, stainless steel, and iron sheet surfaces.

Table 4 Results of the DMRT analysis for the treatment's single effect on the haricot bean's static and dynamic friction coefficients

coefficient	Treatment - Moisture content (db %)				
	9.4	10.6	11.2	12.9	13.5
SFC	0.387 ± 0.012 ^{a*}	0.470 ± 0.010 ^b	0.521 ± 0.015 ^c	0.565 ± 0.019 ^d	0.615 ± 0.009 ^e
DFC	0.400 ± 0.009 ^{**a}	0.436 ± 0.001 ^b	0.464 ± 0.001 ^c	0.501 ± 0.001 ^d	0.535 ± 0.012 ^e
coefficient	Treatment - Contact surface				
	Glass	Aluminum	Plywood	Galvanized	steel Rubber
SFC	0.375 ± 0.002 ^a	0.443 ± 0.014 ^b	0.527 ± 0.008 ^c	0.597 ± 0.020 ^d	0.615 ± 0.011 ^e
DFC	0.374 ± 0.008 ^b	0.350 ± 0.004 ^a	0.463 ± 0.005 ^c	0.517 ± 0.005 ^d	0.631 ± 0.008 ^e
coefficient	Treatment - Sliding velocity (cm s ⁻¹)				
	1	3.5	5.75	9.25	12.5
SFC	0.397 ± 0.001 ^a	0.437 ± 0.001 ^b	0.471 ± 0.001 ^c	0.501 ± 0.011 ^d	0.530 ± 0.011 ^e

Note: * Different letters show significant differences at probability level of 1%. ** Mean ± standard error. DMRT = Duncan's Multiple Range Test.

Effect of treatments - dual interaction effect

Table 5 illustrates the Duncan's Multiple Range Test results of the dual interaction effect of moisture content and contact surface on static friction coefficients of haricot beans. A thorough examination of the data revealed that an increase in moisture content from 9.4% to 13.5% (db) and a switch from a smooth to a coarse contact surface (from glass to rubber) both contributed to a 189% rise in static friction coefficients. A significant difference among static friction coefficients at a probability threshold of 1% is shown by various letters in the Table 5. This

substantial dual interaction effect between moisture content and contact surface on static friction coefficients can be understood as follows: the moisture content of the grain may be transferred to the contact surface and the moistened contact surface functions as a contact surface with distinct properties, causing the static friction coefficients to fluctuate. Therefore, in order to manage static friction coefficients with respect to available facilities, every treatment combination that yields the same effects on static friction coefficients is advised in order to obtain the same frictional behavior of haricot beans.

Table 5 Dual interaction effect of treatments on haricot bean static friction coefficients: DMRT results.

Contact surface	Treatment - variety				
	KAT-B1	KAT-B9	SCR-15	DRK	BZ-2
Glass	0.240 ± 0.019 ^{a*}	0.339 ± 0.017 ^{bc}	0.356 ± 0.022 ^c	0.426 ± 0.010 ^{dc}	0.516 ± 0.011 ^{gh}
Aluminum	0.320 ± 0.010 ^{**b}	0.422 ± 0.009 ^{dc}	0.440 ± 0.012 ^c	0.496 ± 0.019 ^e	0.537 ± 0.016 ^{hi}
plywood	0.413 ± 0.004 ^d	0.469 ± 0.004 ^f	0.518 ± 0.009 ^h	0.586 ± 0.007 ^j	0.651 ± 0.007 ^{kl}
Galvanized steel	0.468 ± 0.017 ^f	0.548 ± 0.011 ⁱ	0.638 ± 0.015 ^k	0.655 ± 0.011 ^{kl}	0.677 ± 0.008 ^{mn}
Rubber	0.495 ± 0.008 ^e	0.573 ± 0.009 ^j	0.651 ± 0.006 ^{kl}	0.662 ± 0.009 ^{lm}	0.693 ± 0.009 ⁿ

Note: *Different letters show significant differences at probability level of 1%. ** Mean ± standard error, DMRT = Duncan's Multiple Range

Table 6, which is based on Duncan's Multiple Range data, shows the dual interaction effect of applied treatments (moisture content, contact surface, and sliding velocity) on the dynamic friction

coefficients of haricot beans. At a probability threshold of 1%, distinct letters in the Table indicate substantial differences among dynamic friction coefficients as impacted by applied treatments.

Similar to static friction coefficients, a physical explanation may be given for the considerable dual interaction effect of moisture content and contact surface on dynamic friction coefficients. Variations in the temperature of the contact surface may also be connected to the important dual interaction effect of sliding velocity and moisture content. Frictional energy changes and releases heat in response to changes in sliding velocity. The heat generated alters the grain moisture content, which alters the dynamic friction coefficients. It is possible to conclude that the heat generated by changing sliding velocity may have an impact on the structure of the contact surface and cause changes in dynamic friction coefficients in the event that there is a considerable dual interaction effect of both the contact surface and sliding velocity on dynamic friction coefficients.

From the standpoint of the user, it is

recommended to change the levels of the treatments with insignificant dual interaction effect on dynamic friction coefficients in Table 6 in order to maximize the performance of the related equipment and structures. Following a simultaneous transition from glass to rubber for the contact surface and from 9.4% to 13.5% moisture content, analysis of the data in Table 6 showed that the dynamic friction coefficients increased by 154.48% (db). Furthermore, when moisture content and sliding velocity were simultaneously raised from 9.4% to 13.5% (db) and from 1 to 12.5 cm s⁻¹, respectively, dynamic friction coefficients increased by 79.88%. Additionally, a 148.92% increase in dynamic friction coefficients was seen while switching from a glass to a rubber contact surface and increasing the sliding velocity from 1 to 12.5 cm s⁻¹.

Table 6 Dual interaction effect of treatments on haricot bean dynamic friction coefficients: DMRT results.

Treatment	Common bean-variety				
Contact surface	KAT-B1	KAT-B9	SCR-15	DRK	BZ-2
Glass	0.290 ± 0.013 ^{a*}	0.321 ± 0.013 ^e	0.370 ± 0.013 ^e	0.426 ± 0.015 ^h	0.465 ± 0.014 ⁱ
Aluminum	0.307 ± 0.007 ^{b**}	0.330 ± 0.006 ^e	0.351 ± 0.005 ^d	0.373 ± 0.005 ^e	0.390 ± 0.007 ^f
plywood	0.409 ± 0.008 ^g	0.441 ± 0.009 ⁱ	0.460 ± 0.010 ^j	0.490 ± 0.011 ^k	0.515 ± 0.010 ^l
Galvanized steel	0.463 ± 0.008 ⁱ	0.495 ± 0.009 ^k	0.514 ± 0.010 ^l	0.544 ± 0.011 ⁿ	0.569 ± 0.010 ^o
Rubber	0.529 ± 0.011 ^m	0.591 ± 0.009 ^p	0.624 ± 0.009 ^q	0.673 ± 0.014 ^r	0.738 ± 0.013 ^s
	Sliding velocity (cm s ⁻¹)				
variety	2.5	3.5	5.75	7.25	10.5
KAT-B1	0.333 ± 0.019 ^a	0.368 ± 0.019 ^b	0.408 ± 0.020 ^c	0.431 ± 0.020 ^d	0.458 ± 0.017 ^f
KAT-B9	0.369 ± 0.022 ^b	0.409 ± 0.022 ^c	0.443 ± 0.021 ^c	0.464 ± 0.020 ^{fg}	0.494 ± 0.020 ^{hi}
SCR-15	0.400 ± 0.021 ^c	0.431 ± 0.021 ^d	0.470 ± 0.020 ^{fg}	0.491 ± 0.020 ^h	0.527 ± 0.022 ^j
DRK	0.426 ± 0.023 ^d	0.471 ± 0.021 ^e	0.498 ± 0.022 ^{hi}	0.539 ± 0.021 ⁱ	0.572 ± 0.023 ^k
BZ-2	0.458 ± 0.022 ^f	0.504 ± 0.023 ⁱ	0.535 ± 0.024 ⁱ	0.580 ± 0.026 ^k	0.599 ± 0.025 ^l
	Contact surface				
Sliding velocity	Glass	Aluminum	plywood	Galvanized	Rubber
1	0.278 ± 0.012 ^a	0.306 ± 0.007 ^b	0.394 ± 0.006 ^f	0.448 ± 0.006 ^h	0.560 ± 0.017 ^m
3.5	0.328 ± 0.014 ^c	0.332 ± 0.006 ^e	0.436 ± 0.008 ^g	0.490 ± 0.008 ⁱ	0.598 ± 0.014 ^o
5.75	0.383 ± 0.014 ^f	0.353 ± 0.006 ^d	0.462 ± 0.007 ⁱ	0.516 ± 0.007 ^k	0.639 ± 0.014 ^p
9.25	0.424 ± 0.015 ^e	0.370 ± 0.007 ^e	0.496 ± 0.009 ^j	0.550 ± 0.009 ^m	0.666 ± 0.017 ^q
12.5	0.459 ± 0.014 ^{hi}	0.389 ± 0.006 ^f	0.528 ± 0.009 ^j	0.582 ± 0.009 ⁿ	0.692 ± 0.017 ^r

Note: *Different letters show significant differences at probability level of 1%. ** Mean ± standard error. DMRT = Duncan's Multiple Range

Effect of treatments - triple interaction effect

The triple interaction of the treatments carried out by Duncan's Multiple Range is shown in a comparison of the mean DFC of haricot beans in Table 7. From the poor frictional condition (contact surface: glass, sliding velocity: 1 cm s⁻¹ and moisture content: 9.4% (db) to the strong frictional condition (contact surface: rubber, sliding velocity: 12.5 cm s⁻¹ and moisture content: 13.5% (db)), a 296.57%

increment of DFC was observed, as shown in the Table. Significant changes at a 1% probability level are represented by different letters in the table. The release of heat alters the grain moisture content, which in turn causes a difference in the contact surface structure and a change in dynamic friction coefficients. These variations in sliding velocity can be used to explain the physical interpretation of this considerable triple interaction effect on dynamic

friction coefficients. Alternatives to apply treatments that resulted in the dynamic friction coefficients with the same letters in Table 7 can be examined in order

to achieve the best frictional condition according to engineering principles.

Table 7 The triple interaction effect of treatments on the dynamic friction coefficients of haricot beans: DMRT data

Contact surface	varieties	Sliding velocity (cm s ⁻¹)				
		2.5	3.5	5.75	7.25	10.5
Glass	KAT-B1	0.204 ± 0.003 ^{a*}	0.245 ± 0.009 ^{bc}	0.294 ± 0.005 ^{ch}	0.328 ± 0.005 ^{im}	0.379 ± 0.005 ^w
	KAT-B9	0.227 ± 0.007 ^{ab*}	0.276 ± 0.004 ^{dc}	0.331 ± 0.006 ⁱ	0.368 ± 0.005 ^{nr}	0.405 ± 0.007 ^s
	SCR-15	0.277 ± 0.005 ^{dc}	0.316 ± 0.010 ^j	0.397 ± 0.012 ^r	0.421 ± 0.007 ^z	0.440 ± 0.010
	DRK	0.319 ± 0.003 ^{se*}	0.388 ± 0.008 ^q	0.414 ± 0.004 ^y	0.482 ± 0.005 ^p	0.528 ± 0.007 ^s
	BZ-2	0.364 ± 0.008 ^{n*}	0.415 ± 0.003 ^{y**}	0.479 ± 0.006 ^k	0.523 ± 0.007 ^{y**}	0.542 ± 0.008 ^{a*}
Aluminum	KAT-B1	0.256 ± 0.005 ^{a*}	0.290 ± 0.005 ^{bc}	0.315 ± 0.002 ^{ch}	0.322 ± 0.002 ^{im}	0.352 ± 0.004 ^{hw}
	KAT-B9	0.286 ± 0.003 ^{ef}	0.312 ± 0.003 ^{fi}	0.327 ± 0.003 ^{il}	0.351 ± 0.001 ^{k*}	0.373 ± 0.001 ^{nr}
	SCR-15	0.316 ± 0.002 ^j	0.332 ± 0.001 ^{im}	0.355 ± 0.001 ^{lp}	0.370 ± 0.001 ^r	0.383 ± 0.001 ^p
	DRK	0.332 ± 0.001 ^{im}	0.357 ± 0.001 ^{mp}	0.377 ± 0.001 ^t	0.391 ± 0.001 ^z	0.406 ± 0.001 ^t
	BZ-2	0.343 ± 0.001 ^{j*}	0.369 ± 0.001 ^{n*}	0.392 ± 0.001 ^{q**}	0.413 ± 0.006 ^{x*}	0.432 ± 0.001 ^{a**}
Plywood	KAT-B1	0.356 ± 0.004 ^{lp}	0.376 ± 0.004 ^s	0.408 ± 0.004 ^w	0.442 ± 0.005 ^{bd}	0.463 ± 0.003 ^{dc}
	KAT-B9	0.374 ± 0.003 [*]	0.418 ± 0.005 ^{y*}	0.455 ± 0.002 ^{k*}	0.466 ± 0.002 ^{im}	0.495 ± 0.002 ^{nr}
	SCR-15	0.390 ± 0.004 ^q	0.433 ± 0.003 ^{ab}	0.458 ± 0.004 ^{fl}	0.478 ± 0.003 ^{k*}	0.538 ± 0.005 ^{ab*}
	DRK	0.408 ± 0.005 ^{wb}	0.459 ± 0.003 ^{fl}	0.484 ± 0.002 ^{kq}	0.535 ± 0.006 ^{za}	0.565 ± 0.003 ^{bq*}
	BZ-2	0.441 ± 0.005 ^{ab**}	0.494 ± 0.002 ^{bd**}	0.504 ± 0.003 ^{tv*}	0.557 ± 0.003 ^{zab}	0.578 ± 0.002 ^{zb**}
Galvanized steel	KAT-B1	0.410 ± 0.004 ^{xb}	0.430 ± 0.004 ^{af}	0.462 ± 0.004 ^{gl}	0.496 ± 0.005 ^{nr}	0.517 ± 0.003 ^{R-X}
	KAT-B9	0.428 ± 0.003 ^{ac}	0.472 ± 0.005 ⁱⁿ	0.509 ± 0.002 ^{pw}	0.520 ± 0.002 ^{vy}	0.549 ± 0.002 ^{YZabq}
	SCR-15	0.444 ± 0.004 ^{dj}	0.487 ± 0.003 ^{iq*}	0.512 ± 0.004 ^{qx}	0.532 ± 0.003 ^{ta}	0.592 ± 0.005 ^{TE,m}
	DRK	0.462 ± 0.005 ^{hl}	0.513 ± 0.003 ^{qx}	0.538 ± 0.002 ^{wa}	0.589 ± 0.006 ^{ef}	0.619 ± 0.003 ^{op**}
	BZ-2	0.495 ± 0.005 ^{mr*}	0.548 ± 0.002 ^{sb*}	0.558 ± 0.003 ^{aq*}	0.611 ± 0.003 ^{st*}	0.632 ± 0.002 ^{sv**}
Rubber	KAT-B1	0.441 ± 0.009 ^{a*}	0.499 ± 0.006 ^{aq}	0.561 ± 0.005 ^{ns}	0.569 ± 0.006 ^{fi}	0.577 ± 0.007 ^{g*}
	KAT-B9	0.532 ± 0.012 ^{tu}	0.568 ± 0.005 ^{bq}	0.590 ± 0.011 ^{yz}	0.616 ± 0.009 ^{ht*}	0.648 ± 0.010 ^{i*}
	SCR-15	0.572 ± 0.005 ^{qr}	0.588 ± 0.003 ^{st*}	0.628 ± 0.010 ^{mr*}	0.652 ± 0.014 ^{kc}	0.682 ± 0.005 ^j
	DRK	0.610 ± 0.048 ^{Ez}	0.639 ± 0.006 ^{mp}	0.675 ± 0.015 ^{zt*}	0.697 ± 0.021 ^{st*}	0.743 ± 0.005 ^{v**}
	BZ-2	0.646 ± 0.005 ^{bd*}	0.697 ± 0.006 ^{tv*}	0.743 ± 0.014 ^{uz**}	0.795 ± 0.004 ^{vt*}	0.809 ± 0.002 ^{k**}

Note: * Different letters show significant differences at probability level of 1%. ** Mean ± standard error.

The regression equations of coefficients of determination all variety grains on various surfaces are presented in Table 8. It is observed from the tables that in all cases the static and kinetic coefficients of friction increased linearly with the increase of moisture content. Both static and kinetic coefficients friction on rubber surface are found to be much higher than those of other surfaces. The

coefficients of friction on galvanized iron and plywood surfaces are similar and closer to each other but little higher than that of glass surface. These data may be used for designing of storage bins, hoppers, chutes, screw conveyors, harvesters, and threshers with the studied materials at different moisture content in the data range.

Table 8 The regression equations and corresponding coefficient of determination (R²) of static and kinetic coefficient of friction with moisture content of grains on various surfaces

variety	Static coefficient of friction		Kinetic coefficient of friction	
	Regression equation	R ²	Regression equation	R ²
<i>Deme</i>	$\mu_{sr} = 0.0035Mc + 0.42$	0.921	$\mu_{sr} = 0.0039Mc + 0.39$	0.986
	$\mu_{gl} = 0.0025Mc + 0.36$	1.000	$\mu_{gl} = 0.0027Mc + 0.34$	0.959
	$\mu_p = 0.0030Mc + 0.36$	0.884	$\mu_p = 0.0033Mc + 0.32$	0.979
	$\mu_g = 0.0027Mc + 0.34$	0.991	$\mu_g = 0.0027Mc + 0.32$	0.999
<i>Belete</i>	$\mu_{sr} = 0.0036Mc + 0.48$	0.998	$\mu_{sr} = 0.0032Mc + 0.46$	0.978
	$\mu_{gl} = 0.0034Mc + 0.39$	0.996	$\mu_{gl} = 0.0025Mc + 0.39$	0.957
	$\mu_p = 0.0032Mc + 0.39$	0.995	$\mu_p = 0.0026Mc + 0.38$	0.992
	$\mu_g = 0.0029Mc + 0.36$	0.998	$\mu_g = 0.0029Mc + 0.36$	0.997
<i>Tafuch</i>	$\mu_{sr} = 0.0034Mc + 0.42$	0.993	$\mu_{sr} = 0.0035Mc + 0.40$	0.976
	$\mu_{gl} = 0.0034Mc + 0.39$	0.996	$\mu_{gl} = 0.0031Mc + 0.34$	0.982
	$\mu_p = 0.0032Mc + 0.39$	0.995	$\mu_p = 0.0028Mc + 0.34$	0.983
	$\mu_g = 0.0029Mc + 0.36$	0.998	$\mu_g = 0.0025Mc + 0.34$	0.997
<i>DAB-B96</i>	$\mu_{sr} = 0.0027Mc + 0.44$	0.993	$\mu_{sr} = 0.0028Mc + 0.43$	0.962
	$\mu_{gl} = 0.0027Mc + 0.34$	0.975	$\mu_{gl} = 0.0030Mc + 0.34$	0.987
	$\mu_p = 0.0031Mc + 0.37$	0.994	$\mu_p = 0.0028Mc + 0.34$	0.940
	$\mu_g = 0.0027Mc + 0.35$	0.986	$\mu_g = 0.0023Mc + 0.35$	0.982
<i>Ado</i>	$\mu_{sr} = 0.0024Mc + 0.49$	0.982	$\mu_{sr} = 0.0033Mc + 0.45$	0.996
	$\mu_{gl} = 0.0024Mc + 0.40$	0.982	$\mu_{gl} = 0.0026Mc + 0.38$	0.972
	$\mu_p = 0.0029Mc + 0.38$	0.988	$\mu_p = 0.0026Mc + 0.38$	0.972
	$\mu_g = 0.0026Mc + 0.36$	0.992	$\mu_g = 0.0025Mc + 0.35$	0.981
<i>DRK</i>	$\mu_{sr} = 0.0028Mc + 0.44$	0.976	$\mu_{sr} = 0.0033Mc + 0.42$	0.979
	$\mu_{gl} = 0.0025Mc + 0.39$	0.998	$\mu_{gl} = 0.0031Mc + 0.34$	0.953
	$\mu_p = 0.0029Mc + 0.38$	0.986	$\mu_p = 0.0028Mc + 0.35$	0.929
	$\mu_g = 0.0027Mc + 0.35$	0.934	$\mu_g = 0.0025Mc + 0.34$	0.996
<i>BZ-2</i>	$\mu_{sr} = 0.0028Mc + 0.47$	0.993	$\mu_{sr} = 0.0032Mc + 0.45$	0.998
	$\mu_{gl} = 0.0029Mc + 0.39$	0.998	$\mu_{gl} = 0.0028Mc + 0.37$	0.988
	$\mu_p = 0.0030Mc + 0.38$	0.990	$\mu_p = 0.0030Mc + 0.36$	0.995
	$\mu_g = 0.0025Mc + 0.36$	0.981	$\mu_g = 0.0026Mc + 0.35$	0.998

Note: μ_{sr} = coefficient of friction for steel rubber, μ_{gl} = coefficient of friction for galvanized iron, μ_p = coefficient of friction for plywood, and μ_g = coefficient of friction for glass, Mc = moisture content, %(wb).

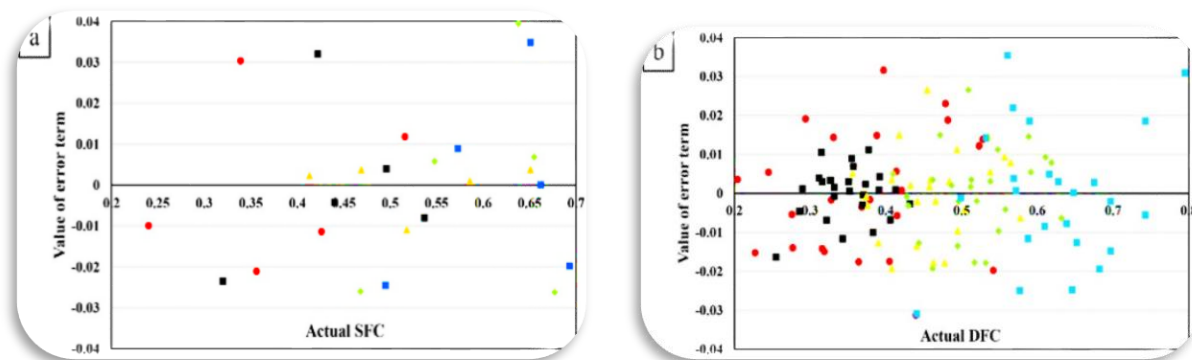


Figure 3 Error term value distribution in several linear regression models constructed for haricot bean friction coefficient prediction, SFC (a) and DFC (b). (Glass, aluminum, plywood, galvanized steel and rubber surface)

For static and dynamic friction coefficients prediction, multiple linear regression models were distribution of the erroneous term values appear to have occurred at random and no trend was found, based on the data shown in Figure 3. As a result, actual data had no bearing on the multiple linear regression models' error term values. Based on the figure, the Value of error term and standard deviation for the static friction coefficients were determined to be 0.015 and 0.012, respectively. Regarding dynamic friction coefficients, these figures were discovered to be 0.010 and 0.008.

In Figure 4, the constructed multiple linear regression models for haricot bean static friction coefficients prediction are displayed. The static

friction coefficient has increased linearly with increasing moisture content on each contact surface, according to the 2DC in the figure. The interplay of contact surface and moisture content on static friction coefficients is shown by the contour plot result of multiple linear regressions modeling, as shown in Figure 4. The graphic illustrates how a rise in moisture content from 9.4% to 13.5% (db) and a switch from glass to rubber for the contact surface led to an integrated increment of static friction coefficients starting at the lowest value (0.6). This aligns with the findings of the statistical examination of the moisture content and contact surface dual interaction effect on static friction coefficients (dual interaction effect Section).

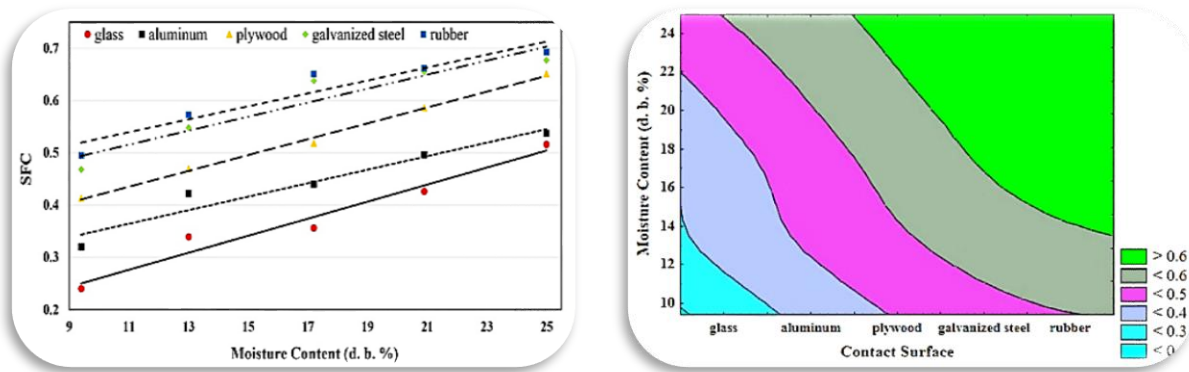


Figure 4 Common bean static friction coefficient modeling using multiple linear regressions on the relevant contact surfaces

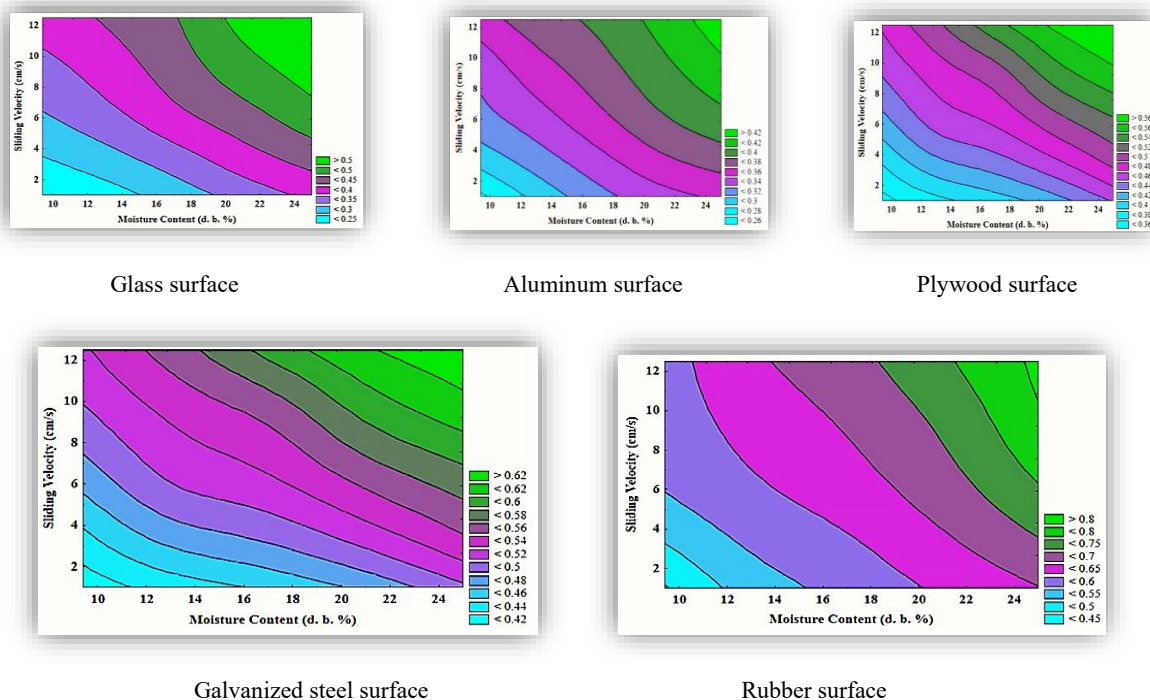


Figure 5 Common bean DFC modeling using multiple linear regressions on several surfaces

Figure 5 presents a graphic representation of the developed multiple linear regression models for haricot bean dynamic friction coefficients prediction with respect to each contact surface. The concept of the response of the model output to the input variables is made clearer by the 3DCs for dynamic friction coefficients prediction. It appears that as sliding velocity and moisture content increased, the dynamic friction coefficients rose linearly. The model output is shown by the contour plot in Figure 5, which is based on the graphical reflection of the relationship between sliding velocity and moisture content. The relationship between sliding velocity and moisture content on dynamic friction coefficients has been consistent, as the graphs demonstrate. The moisture content and sliding velocity increased simultaneously, causing the dynamic friction coefficients to fluctuate more. This modeling result correlates with the dual interaction effect statistical analysis on dynamic friction coefficients (dual interaction effect Section) for sliding velocity and moisture content.

In summary, the results of the multiple linear regression modeling indicate that there is no need to evaluate static and dynamic friction coefficients because the models can accurately predict the friction coefficients of haricot beans under processing and storage conditions. Moreover, the models provide a realistic physical representation of how treatments affect static and dynamic friction coefficients. When managing and controlling static and dynamic friction coefficients of haricot bean in real-world situations the ability to perceive physical cues is useful.

4 Conclusion

This study offers some insightful data regarding the static and dynamic friction coefficients of haricot beans as impacted by various treatments. The results allow for the significant deduction of the following conclusions:(1) The static and dynamic friction coefficients were distinct for all experimental condition and varied with changes in sliding velocity, moisture content, and contact surface. (2) At a 1%

probability level, the SE and dual interaction effect, as well as the single effect, dual interaction effect, and triple interaction effect of the treatments, on static and dynamic friction coefficients, were significant. (3) On the static friction coefficients, the dual interaction effect of treatments was more successful than the single effect of the contact surface, which was followed by moisture content. Similar to this, in the case of dynamic friction coefficients, sliding velocity and moisture content were ranked higher than triple interaction effect of treatments, dual interaction effect, and single effect of contact surface. (4) The static friction coefficients rose linearly with increasing moisture content for all evaluated contact surface. As the moisture content and sliding velocity increased, the dynamic friction coefficients also increased linearly. (5) Using the multiple linear regressions modeling technique, the static and dynamic friction coefficients were successfully modeled for each contact surface. The constructed models' predictive abilities were assessed using average statistical parameters, which were $R^2 = 0.941$, $RMSE = 0.02281$, and $MRDM = 3.151\%$ for static friction coefficients and $R^2 = 0.968$, $RMSE = 0.01295$, and $MRDM = 2.153\%$ for dynamic friction coefficients. Based on experimental levels of moisture content and sliding velocity, the created multiple linear regression models are effective tools for directly determining the friction coefficients of common bean on examined contact surfaces, without the requirement for actual static and dynamic friction coefficients measurements. Conclusions given above are useful guidelines for optimizing processing conditions and storage apparatus, including grain bins. The present study suggests that the ANOVA and DMRT-based analysis method employed in this article be extended to examine the impact of significant treatments on the static and dynamic friction coefficients of other significant major legume crops.

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