Short Research Article

Friction Coefficients of Local Food Grains on Different Structural Surfaces

Knowledge of friction coefficient of agricultural commodities on various structural surfaces is imperative in the design and material selection for postharvest handling, transportation, processing and storage equipment. This paper presents the friction coefficients of local food grains on different structural surfaces as a function of moisture content. The experiment was conducted using a Complete Randomized Design (CRD) in a factorial treatment design to evaluate the influence of different structural surfaces (glass, mild steel, plastic, ply-board, and aluminium) and moisture content levels (6, 12, 18, and 24% wet basis) on the coefficient of friction of selected local grains (benniseed, finger millet, pearl millet, and hungry rice). Results obtained indicate that the friction coefficient (μ) of the studied grain samples increased linearly with increase in moisture level for all the tested structural surfaces. Within the range of the studied moisture content, benniseed exhibited the highest μ-value ($0.526 \pm 0.031 \le \mu \le 0.784 \pm 0.157$) on ply-board, whereas hungry rice had the lowest value ($0.248 \pm 0.018 \le \mu \le 0.527 \pm 0.023$) on glass material. Amongst the tested metal surfaces, aluminum had the lowest μ-value (0.236) at 6% moisture content. The effect of structural surfaces and moisture contents as well as their interactions on friction coefficient were statistically significant at P =.05 for all the studied grain samples. High values of correlation coefficient (R^2) > 0.95 were obtained to indicate strong correlation between μ-values and experimental factors. A low coefficient of variation (CV) of 2.75% was obtained to show high experimental reliability.

***Keywords:** Benniseed, millet, hungry rice, moisture content, friction coefficient, structural surface.*

1. INTRODUCTION

Food grains are categorized based on their morphological differences, and their frictional characteristics can vary significantly. The economic role of grain products and the increase in development of advanced technologies for food production, transportation, processing, storage, quality evaluation, development, marketing and consumption are increasing in recent years in Nigeria as a result of some degree of agricultural mechanization. Therefore, a fundamental understanding of the physical and engineering properties of food grains is important in confronting the challenging problems of grain handling, processing, and storage [1]. Benniseed (*Sesame)* is a member of *Pedaliaceae* family and one of the most ancient oilseed crops known to mankind. It plays an important role in human nutrition, because it contains about 51% oil, 17-19% protein and 16-18% carbohydrate and can also be consumed [2]. It has wide domestic and industrial applications, which includes production of margarine, confections, canned sardine, cooking oil, salad oil, lamp oil, corned beef, soap making, paint and ink, etc. as well as culinary and medicinal purposes. In Nigeria, the benniseed is either consumed fresh, dried, fried or blended with sugar. It is also used as a paste in some local delicacies.

Millet is a generic name for a numberof small - seeded varieties of cereals or grains grown mainly on marginal lands in dry temperate, subtropical and tropical regions. It belongs to the family *Gramineae* and widely cultivated all over the globe for food and fodder. Pearl millet (*Pennisetum glaucum*) and Finger millet (*Eleusine coracana*) are amongst the most widely cultivated varieties of millet in the world. In Nigeria, pearl millet is used in making a popular fried cake known as '*masa'*. Its flour is also used in the preparation of '*tuwo' drink*, a thick binding paste. In Northern Nigeria, it is often ground into flour, rolled into large balls, parboiled, liquefied into a watery paste using fermented milk and then consumed as a beverage, known as *'fura'*. Pearl millet is amongst the most nutritious food grains of the major cereals that is equivalent to maize which has more protein content and quality than sorghum. On the other hand, the higher nutritional contents and outstanding properties of finger millet as a subsistence food crop stands it unique amongst the cereals. It is rich in calcium, dietary fiber, phytates, protein, minerals, phenolics and also a rich source of thiamine, riboflavin, iron, methionine, isoleucine, leucine, phenylalanine and other essential amino acids. The abundance of these phytochemicals enhances the nutraceutical potential of finger millet, thus making it a powerhouse of health benefiting nutrients [3].

Hungry rice/acha (*Digitaria exilis*) is a cereal and a staple food which grows well in some parts of Nigeria. Hungry rice has two major varieties: white variety - *Digitaria exilis* (acha) and black variety - *Digitaria iburua* (iburu). The white variety is the most widely used on the upland plateau of central Nigeria, whereas the black variety is used in Jos-Bauchi Plateau areas of Nigeria. Acha and rice are technologically used in similar ways to rice. The two grain varieties (acha and iburu) have minimal processing time because of their grain size and location of constituents. They have different applications especially in nutrition, medicine, domestic and industry.

Given the varying domestic and industrial applications of grain products, it is transported all over Nigeria by cargo-trucks because of its rising demand and viable qualities produced. Grain handling could pose a challenge to flowability over surfaces due to caking, clustering and sticking during long distant transportation. This needs extra labour, machinery and time, thereby making grain processing operation time and labour intensive; thus gross economic loss [4, 5]. The type and components of grain handling system are determined by the flow characteristics of grain materials on surfaces in contact, which is a function of friction coefficient and angle of repose. The physical properties of the grain product as well as the textural characteristics of the storage or contact wall determines its coefficient of friction. Yanada and Sekikawa [6] noted that friction is one important variable that affects system efficiency and motion of surfaces in mutual contact. The frictional behaviour of grains between surfaces in contact can be influenced by their physical and chemical characteristics [7].

In addition, friction can increase power requirement as a result of heat generation between grains in relative motion [7]. Influence of different structural surfaces and moisture levels on coefficients of friction have been reported for various food grains. A linear correlation between moisture content and coefficient of friction on different surfaces has been observed [7, 8, 9, 10, 11]. Previous studies indicated that increase in friction coefficient with increasing moisture content may be as a result of increase in forces of cohesion and adhesion acting on the surface of contact, the nature of structural material, and inter-particulate properties [11, 12]. Reports on the determination of static coefficient of friction of grains and nuts on several structural surfaces like glass, jute bag, mild steel, stainless steel, galvanized steel, aluminum, polythene, etc., using either the method of tilting table test or method of inclined plane have made by several researchers [7, 8, 13, 14]. It is noted that these several structural materials, which are commonly used for construction of grain handling, processing and storage equipment should be selected based on their low frictional coefficients I contact with grain products.

However, data on physical and chemical properties of various new varieties of local food grains, as well as their flow behaviour on different structural surfaces at varying moisture levels, are essential for the purposes of selection and design of efficient postharvest technologies for handling, processing and storage of grain products. There has been insufficient baseline data in the literature or extensive research carried out on the variation of friction coefficient of local food grains on most structural materials at different moisture content levels. This study was undertaken to determine the variation of friction coefficients of different local food grains (benniseed, finger millet, pearl millet, and hungry rice) with varying moisture contents and structural surfaces.

2. MATERIALS AND METHOD

2.1 Equipment Description

The equipment developed to measure the friction coefficient is as shown in Fig. 1. It is made of 1.5" angle-iron. It consists of a 1.5" angle iron frame support of 500mm in height and a stationary platform, 450mm in length and 300mm in width. The top of the device (tilting table/plate) was made of a lighter material of 1" angle iron, to make provision for easy tilting of the plate and to prevent wear and tear of the screw thread during up-and-down lifting action. By rotating the threaded screw in a clockwise direction, tilting of the table is realized and the free end of the tilting table is lifted at an inclined angle. Below the stationary plate, the screw unit is vertically fixed in the center of the device. A standard protractor was used to measure the inclined angle, with its zero mark placed to flush with the testing surface in a horizontal position. Hinges were used to join the stationary platform and tilting table together at one side of the device. Different structural surfaces (glass, ply-board, aluminum, plastic, and mild steel) to be tested can be changed with ease on the tilting table. These testing surfaces were selected based on surface conditions and degree of deformation that surface pressure and adhesive forces alter the frictional characteristics of food grains.

2.2 Experimental Procedure

The materials used for this study were benniseed (*sesamum indicum L.*), finger millet (*Eleusine coracana*), Pearl millet (*Pennisetum glaucum*), and hungry rice (*Digitaria exilis*), purchased from new market, Aba, Nigeria. The standard oven method at 103^{o}C for 72 hours was adopted for determination of moisture contents of the grains at purchase [15, 16]. Calculated amount of water was added to the grain samples in order to alter the grain moisture contents to the different selected levels for the study [10]. Thereafter, the samples were packaged in a polythene bags and stored in a refrigerator at 10^{o}C for 48 hours [17] to ensure equilibration of moisture. The different selected moisture levels for the tests were 6%, 12%, 18% and 24% wet basis, obtained using Eq. (1). These moisture content levels were adequate since handling and storage of the studied grain samples are mostly carried in within this moisture content range [8].

$$M_w = \frac{M_s(M_2 - M_1)}{100 - M_2} \qquad (1)$$

Where: M_w = mass of water (kg), M_s = mass of grain sample to be processed (kg), M_1 = initial moisture content (%wb), M_2 = desired final moisture content (%wb).

Each sample was tested on the five different structural surfaces to measure the static coefficient of friction. For each test, the desired surface was selected and placed on an adjustable surface of the tilting table (Fig. 1). Prepared grain samples were poured into a container placed on the testing surface with minimum clearance from the testing surface. The knob of the screw unit was gently turned clockwise to tilt the table until the grain samples began to slide down the table as a result of friction force between the grain samples and structural surface being overcome by gravity. The vertical distance moved by the adjustable plate was measured and the tangent of the slope angle was read off, thus the static coefficient of friction was calculated using Eq. (2). Similar procedure was adopted by Nwakonobi and Onwualu [10] and Ezeaku [18].

$$\mu = \tan\emptyset \tag{2}$$

Where: $\emptyset$ is the angle of tilt.

The process was replicated three times for each experimental treatment and the mean calculated for further analyses. The structural surfaces used for the study were glass, metal sheet, aluminium, plywood and plastic. A 5 x 4 x 4 factorial experiment in Completely Randomized Designed (CRD) was adopted to study the influence of moisture content and structural surface on the friction coefficient of each of the selected grain samples (Table 1). Data obtained were subjected to statistical analysis using standard analysis of variance (ANOVA) methods to determine the degree of influence of the experimental variables and interactions between the properties studied. The range of experimental values of the coefficient of variation which yield a high reliability index were also determined.

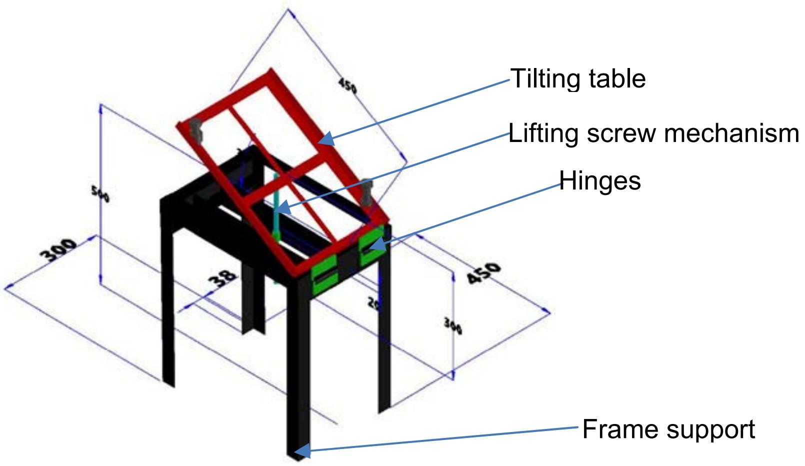


Fig. 1. Isometric view of the tilting table apparatus for determining the coefficient of friction.

Table 1. Experimental layout of a factorial treatment design.

Structural surface	**Grain sample**	**Moisture content (%w.b)**				**Total**	**Mean**
		6	**12**	**18**	**24**		
Glass (G)	G_1	$6GG_1$	$12GG_1$	$18GG_1$	$24GG_1$		
	G_2	$6GG_2$	$12GG_2$	$18GG_2$	$24GG_2$		

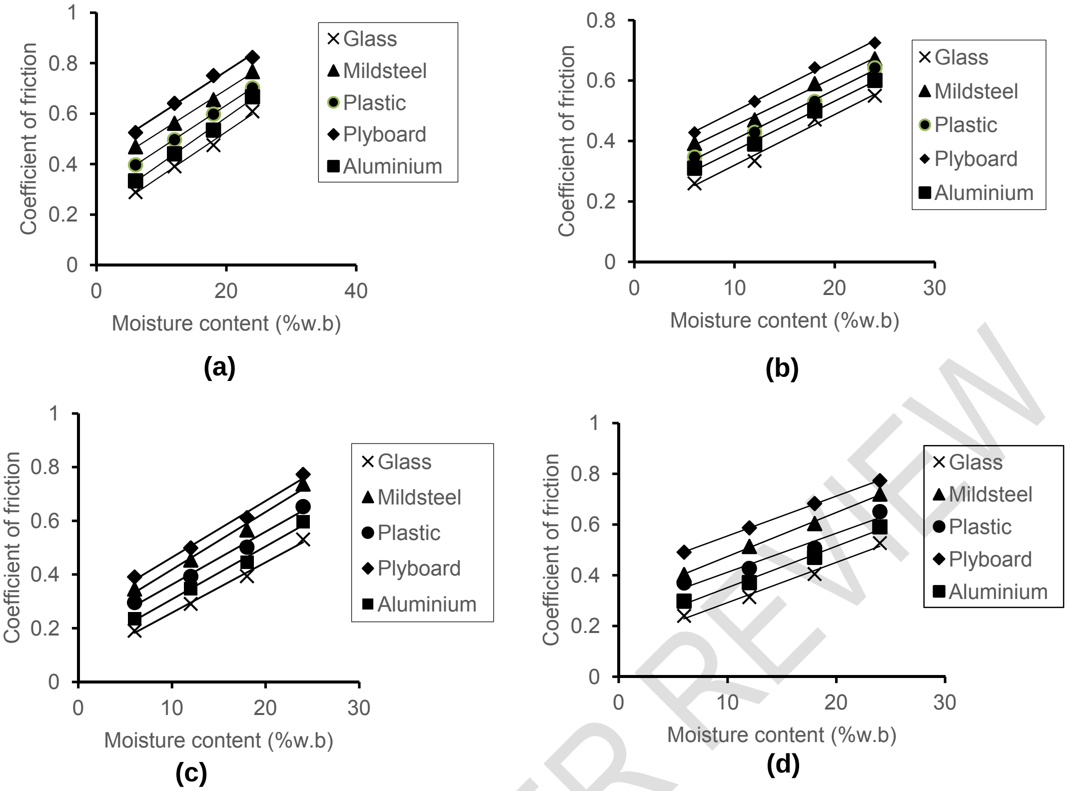
	G_3	$6GG_3$	$12GG_3$	$18GG_3$	$24GG_3$
	G_4	$6GG_4$	$12GG_4$	18GG4	$24GG_4$
	Total				
	Mean				
Ply-board (P)	G_1	$6PG_1$	$12PG_1$	$18PG_1$	$24PG_1$
	G_2	$6PG_2$	$12PG_2$	$18PG_2$	$24PG_2$
	G_3	$6PG_3$	$12PG_3$	$18PG_3$	$24PG_3$
	G_4	$6PG_4$	$12PG_4$	$18PG_4$	$24PG_4$
	Total				
	Mean				
Aluminium (A)	G_1	$6AG_1$	$12AG_1$	$18AG_1$	$24AG_1$
	G_2	$6AG_2$	$12AG_2$	$18AG_2$	$24AG_2$
	G_3	$6AG_3$	$12AG_3$	$18AG_3$	$24AG_3$
	G_4	$6AG_4$	$12AG_4$	$18AG_4$	$24AG_4$
	Total				
	Mean				
Plastic (Pl)	G_1	$6PlG_1$	$12PlG_1$	$18PlG_1$	$24PlG_1$
	G_2	$6PlG_2$	$12PlG_2$	$18PlG_2$	$24PlG_2$
	G_3	$6PlG_3$	$12PlG_3$	$18PlG_3$	$24PlG_3$
	G_4	$6PlG_4$	$12PlG_4$	$18PlG_4$	$24PlG_4$
	Total				
	Mean				
Mild steel (M)	G_1	$6MG_1$	$12MG_1$	$18MG_1$	$24MG_1$
	G_2	$6MG_2$	$12MG_2$	$18MG_2$	$24MG_2$
	G_3	$6MG_3$	$12MG_3$	$18MG_3$	$24MG_3$
	G_4	$6MG_4$	$12MG_4$	$18MG_4$	$24MG_4$
	Grand Total				

G_1 = Benniseed, G_2 = Finger millet, G_3 = Pearl millet, G_4 = Hungry rice; replications = 3.

3. RESULTS AND DISCUSSION

3.1 Variation of Coefficient of Friction with Moisture Content on Different Structural Surfaces

Figures 2a - d depict the results of determination of the coefficient of friction (μ) of benniseed, finger millet, Pearl millet, and hungry rice at different moisture content levels and structural surfaces, respectively. The coefficient of friction increased linearly with increasing amount of moisture content for all the tested structural surfaces and grain products, with benniseed and pearl millet exhibiting the highest and lowest increase on plywood, respectively. The values for the coefficient of friction ranged between $0.283 \pm 0.014 \le \mu \le 0.784 \pm 0.157$, for benniseed; $0.245 \pm 0.016 \le \mu \le 0.684 \pm 0.243$, for finger millet; $0.221 \pm 0.016 \le \mu \le 0.643 \pm 0.114$, for pearl millet, and $0.248 \pm 0.018 \le \mu \le 0.731 \pm 0.248$, for hungry rice for a moisture range of 6 – 24% w.b. Previous studies have shown that linear increase in μ -values with moisture content may be attributed to increase in inter-particulate properties and adhesive forces between the grain samples and the contact surfaces as the sample moisture content increases, as well as inability of wet and heavy grain samples to easily slide over the testing surfaces [7, 8].



(a) (b)

(c) (d)

Fig. 2. Effect of moisture content and structural surfaces on coefficient of friction of: (a) benniseed, (b) finger millet, (c) Pearl millet, and (d) hungry rice.

The μ-values of benniseed can be compared to values of 0.279 – 0.569 for cowpea within the moisture content range of 10 – 28% [7]. Obetta and Onwualu [19] obtained similar close range values (0.267 ≤ μ ≤ 0.697) for finger millet. Nwakonobi and Onwualu [10] reported pearl millet μ-value ranges of 0.26 ± 0.06 ≤ μ ≤ 0.35 ± 0.07 and 0.22 ± 0.02 ≤ μ ≤ 0.3 ± 0.02 on steel and plastic surfaces, respectively over a moisture range of 21% ≤ M ≤ 34.7%, compared with mild steel (0.346 ± 0.020 ≤ μ ≤ 0.566 ± 0.104), plastic (0.299 ± 0.018 ≤ μ ≤ 0.502 ± 0.101), over a moisture range of (6% ≤ M ≤ 24% w.b) in the present study. The marginal difference observed in the results obtained is attributed to difference in accuracy of the testing apparatus, environmental condition under which the tests were carried out, variation in surfaces used and irregularity in agricultural products.

However, the relationship between the coefficient of static friction and moisture content as well as their corresponding coefficient of determination for each of the tested structural surfaces and grain samples are presented in Table 2. It is evident that the moisture content levels for benniseed sample correlated well with the structural surfaces, thus high R^2-value > 0.98. This high R^2-value indicates strong correlation between static coefficient of friction and moisture content levels. Also the results obtained for benniseed, as stated earlier showed higher μ-values than other grain samples. This is probably due to the higher bulk density of benniseed sample and also the inter-particulate forces of cohesion and adhesion amongst the granular materials and on the surface of contact [11]. The applicability of the regression equations are limited to the grain sample moisture range tested (6 – 24%w.b).

Table 2. Regression equations of the coefficient of friction and moisture content of the studied grain samples at varying structural surfaces.

Grain sample	Structural Surface	Regression Equation	Correlation Coefficient (R^2)
Benniseed	Glass	$\mu_{\mathrm{bennissed}}$= 0.0137M + 0.202	0.9897
	Mild steel	$\mu_{\mathrm{bennissed}}$ = 0.0155M + 0.367	0.9978
	Plastic	$\mu_{\mathrm{bennissed}}$ = 0.0148M + 0.332	0.9987
	Ply board	$\mu_{\mathrm{bennissed}}$= 0.0152M + 0.446	0.9960
	Aluminum	$\mu_{\mathrm{bennissed}}$ = 0.0147M + 0.257	0.9989
Finger millet	Glass	$\mu_{\mathrm{F.millet}}$ = 0.0157M + 0.145	0.9913
	Mild steel	$\mu_{\mathrm{F.millet}}$ = 0.0170M + 0.291	0.9969
	Plastic	$\mu_{\mathrm{F.millet}}$ = 0.0165M + 0.242	0.9956
	Ply board	$\mu_{\mathrm{F.millet}}$ = 0.0167M + 0.331	0.9963
	Aluminum	$\mu_{\mathrm{F.millet}}$ = 0.0164M + 0.217	0.9962
Pearl millet	Glass	$\mu_{\mathrm{P.millet}}$ = 0.0198M + 0.205	0.9617
	Mild steel	$\mu_{\mathrm{P.millet}}$ = 0.0220M + 0.187	0.9718
	Plastic	$\mu_{\mathrm{P.millet}}$ = 0.0199M + 0.159	0.9888
	Ply board	$\mu_{\mathrm{P.millet}}$ = 0.0225M + 0.219	0.9916
	Aluminum	$\mu_{\mathrm{P.millet}}$ = 0.0187M + 0.127	0.9799
Hungry rice	Glass	$\mu_{\mathrm{H.rice}}$ = 0.0163M + 0.188	0.9886
	Mild steel	$\mu_{\mathrm{H.rice}}$ = 0.0174M + 0.300	0.9979
	Plastic	$\mu_{\mathrm{H.rice}}$ = 0.0154M + 0.258	0.9557
	Ply board	$\mu_{\mathrm{H.rice}}$ = 0.0181M + 0.3745	0.9915
	Aluminum	$\mu_{\mathrm{H.rice}}$ = 0.0159M + 0.1335	0.9872

M = Moisture content (% w.b) μ= coefficient of friction.

It is evident from Figure 2 and Table 2, that the coefficient of friction of agricultural products does not only depend on its moisture content but also on the structural surfaces in contact with the product [10]. Amongst the tested metal structural surfaces, aluminum had the lowest coefficient of friction for all the grain samples at all moisture levels. This implies more easy flow of grains on aluminum surface as a result less resistive force. Sacilik *et al*. [20] worked on galvanized metal and hemp seeds and reported similar observation for a range of moisture level of 8.62 - 20.88%. Benniseed showed the highest increase in the coefficient of friction on all tested structural surfaces and moisture levels, followed by pearl millet, hungry rice, and finger millet, in that order.

At a moisture range of 6 – 24% w.b, the highest values of coefficient of friction for benniseed (0.526 ± 0.031 ≤ μ ≤ 0.784 ± 0.157) were obtained with ply-board. This was followed by mild steel (0.469 ± 0.021 ≤ μ ≤ 0.767 ± 0.170), plastic (0.397 ± 0.023 ≤ μ ≤ 0.702 ± 0.158), aluminum (0.344 ± 0.018 ≤ μ ≤ 0.667 ± 0.211), and glass (0.289 ± 0.014 ≤ μ ≤ 0.609 ± 0.019). For finger millet, the highest μ-values were obtained with ply board (0.428 ± 0.141 ≤ μ ≤ 0.725 ± 0.243). This was followed by mild steel (0.392 ± 0.024 to 0.672 ± 0.213), plastic (0.347 ± 0.023 ≤ μ ≤ 0.642 ± 0.201), aluminum (0.319 ± 0.021 ≤ μ ≤ 0.601 ± 0.200) and glass (0.245 ± 0.016 ≤ μ ≤ 0.55 ±0.024). For pearl millet, the highest μ-values were also obtained with ply-board (0.391 ± 0.0.016 ≤ μ ≤ 0.773 ± 0.114), followed by mild steel (0.346 ± 0.020 ≤ μ ≤ 0.737 ± 0.104), plastic (0.296 ± 0.018 to 0.653 ± 0.101), aluminum (0.236 ± 0.017 ≤ μ ≤ 0.596 ± 0.031) and glass (0.191 ± 0.016 ≤ μ ≤ 0.531 ± 0.022). For hungry rice the highest μ-values were obtained with ply board (0.491 ± 0.141 ≤ μ ≤ 0.773 ± 0.248), followed by mild steel (0.403 ± 0.025 ≤ μ ≤ 0.702 ± 0.244), plastic (0.370 ± 0.022 ≤ μ ≤ 0.651 ± 0.222), aluminum (0.298 ± 0.024 ≤ μ ≤ 0.591 ± 0.224) and glass (0.248 ± 0.018 ≤ μ ≤ 0.527 ± 0.023). These have implications for the selection of these structural materials in design of equipment for handling, processing and storing these agricultural granular materials in particular and other materials in general.

The results of statistical analysis as given in Table 3, indicate that the influence of moisture content on coefficient of friction on glass, mild steel, plastic, ply-board, and aluminum surfaces for Benniseed sample was highly significant at $P < 0.05$. Statistical values of "Prob > F" less than 0.05 show that moisture content and structural surfaces are significant for any grain sample. Interaction effects of moisture content and structural surfaces on friction coefficients were also found to be highly significant ($P = .05$). Similar observations were recorded for Finger millet, Pearl millet and Hungry rice samples. Moisture content and structural surfaces have significant effect on the friction coefficient of all the studied grain samples. This corroborated the linear correlation observed in Figure 2. Bart-Plange *et al.* [8] reported similar observation for plywood, galvanized steel and rubber surfaces with cowpea, maize and groundnut. The coefficient of variation (CV) values according to Nwakuba *et al.* [21] should be < 4% but were observed to be 2.75%. This is an indication of the reliability of the experimental data.

Table 3. Analysis of variance for Benniseed sample.

Source of variation	Degree of freedom	Sum of squares	Mean square	F-value	P-value Prob > F
Moisture content (M)	3	0.082	0.027	9.310	< 0.0002*
Structural surface (S)	4	3.527	0.882	304.14	< 0.0001*
Interaction (M x S)	12	0.227	0.019	6.55	0.0004*
Error	38	0.11	0.0029	--	--
Total	59	3.946	--	--	--

*Significant CV = 2.75%

Knowledge of friction coefficient and other physical attributes of local food grains are of great importance in the design and construction of hoppers, silos and other storage systems, as well as processing and grain handling equipment. Variations in the coefficient of friction of the studied grains could be a function of the experimental method adopted for its determination and the grain functional characteristics [7]. Generally, results obtained inferred that when a similar handling system is adopted for the four grain samples studied, pearl millet would have a higher tendency to flow more easily than other grain products because of its lowest μ-value on all the tested structural surfaces (Figure 2c). Glass, which generally yielded the lowest μ-value for the grain products would also offer least product flow resistance. However, the slippery nature of glass surface is attributed to the major reason for its low μ-value as against the other studied structural surfaces at varying grain moisture levels. The study has also shown that it is imperative to comparatively apply these empirical data than precisely because of changes in handling of food grains, materials of construction, varieties, physical properties, and method of determination of friction coefficient. It is needful therefore, to develop standard technique for friction coefficient determination to eradicate discrepancies in experimental results.

4. CONCLUSION

The study on the effect of varying moisture contents and structural surfaces on friction coefficient of benniseed, pearl millet, hungry rice, and finger millet revealed the following conclusions:

i. The coefficient of friction of the studied grain samples increased linearly with increase in moisture level for all the tested structural surfaces.
ii. At moisture content range of 6 – 24% w.b, benniseed grain exhibited the highest coefficient of friction on ply-board in the range of $0.526 \pm 0.031 \leq \mu \leq 0.784 \pm 0.157$, in comparison to the lowest value of glass which ranged between $0.248 \pm 0.018 \leq \mu \leq 0.527 \pm 0.023$ for hungry rice.
iii. Ply-board exhibited the highest values of coefficient of friction, followed by mild steel, plastic, aluminum, and glass, in that order for all the test grain samples.
iv. Statistical analysis showed that structural surfaces and moisture content effects on the coefficient of friction of the studied grains were highly significant at $P < 0.05$. Their interactions were also statistically significant.
v. Significant differences exist from the statistical analyses conducted amongst the coefficient of friction of benniseed, pearl millet, hungry rice, and finger millet on the five structural surfaces.
vi. Strong correlation exits between coefficient of friction, moisture content levels and the different structural surfaces as indicated by R^2-values > 0.95. The reliability of experiment was indicated by a low CV, less than 4%.
vii. In order to reduce frictional losses and enhance the efficiency of grain handling, processing and storing operations, materials with low friction coefficients with food grains are desirable to be selected.

COMPETING INTERESTS

Authors have no conflict of interest.

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