A comprehensive investigation on static and dynamic friction coefficients of wheat grain with the adoption of statistical analysis

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Abstract

This paper deals with studying and modeling static friction coefficient (SFC) and dynamic friction coefficient (DFC) of wheat grain as affected by several treatments. Significance of single effect (SE) and dual interaction effect (DIE) of treatments (moisture content and contact surface) on SFC and, SE, DIE, and triple interaction effect (TIE) of treatments (moisture content, contact surface and sliding velocity) on DFC were determined using statistical analysis methods. Multiple linear regression (MLR) modeling was employed to predict SFC and DFC on different contact surfaces. Predictive ability of developed MLR models was evaluated using some statistical parameters (coefficient of determination ($R^2$), root mean square error (RMSE), and mean relative deviation modulus (MRDM)). Results indicated that significant increasing DIE of treatments on SFC was 3.2 and 3 times greater than significant increasing SE of moisture content and contact surface, respectively. In case of DFC, the significant increasing TIE of treatments was 8.8, 3.7, and 8.9 times greater than SE of moisture content, contact surface, and sliding velocity, respectively. It was also found that the SE of contact surface on SFC was 1.1 times greater than that of moisture content and the SE of contact surface on DFC was 2.4 times greater than that of moisture content or sliding velocity. According to the reasonable average of statistical parameters ($R^2 = 0.955$, RMSE $= 0.01788$ and MRDM $= 3.152$%), the SFC and DFC could be successfully predicted by suggested MLR models. Practically, it is recommended to apply the models for direct prediction of SFC and DFC, respective to each contact surface, based on moisture content and sliding velocity.

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Nomenclature

| Symbol | Definition |
|--------|------------|
| FF     | friction force (N) |
| FC     | friction coefficient |
| S      | sphericity (%) |
| W      | width (mm) |
| \( W_{wp} \) | mass of added distilled water (g) |
| \( W_i \) | initial mass of sample (g) |
| \( x_1 \) | 1st MLR model variable |
| \( x_2 \) | 2nd MLR model variable |
| \( x_n \) | nth MLR model variable |
| \( E \) | error term of MLR model |
| \( \text{FC}_{\text{average}} \) | average of actual friction coefficient |
| \( M_i \) | initial moisture content of sample (d. b.%) |
| \( M \) | mean of used data |
| CV     | coefficient of variation (%) |
| \( \text{FC}_{\text{max}} \) | maximum friction coefficient |
| C      | contribution of variation (%) |
| CNU    | coefficient of non-uniformity (%) |
| NF     | normal force (N) |
| SSv    | sum of square of variation |
| \( \text{FC}_{\text{min}} \) | minimum friction coefficient |
| \( SS_t \) | total sum of square |
| SD     | standard deviation |
| \( \text{FC}_{\text{act,i}} \) | ith actual friction coefficient |
| \( \text{FC}_{\text{pre,i}} \) | ith predicted friction coefficient |
| \( N \) | number of data |
| \( a_n \) | nth MLR model coefficient |
| \( a_2 \) | 2nd MLR model coefficient |
| \( a_1 \) | 1st MLR model coefficient |
| \( a_0 \) | MLR model constant |
| \( S_a \) | surface area (mm²) |
| T      | thickness (mm) |
| L      | length (mm) |
| \( D_{G} \) | GMD (mm) |
| RMSE   | root mean square error |
| MRDM   | mean relative deviation modulus (%) |

Introduction

Wheat is a dominate major crop in human food. The crop is widely cultivated throughout the world. Hence, investigation of different aspects of wheat in planting, harvesting, transporting, storing and processing stage is of great importance in management of its production and preservation.

Physical properties of agricultural products are frequently used for designing of agricultural machinery and equipment of related post-harvest industries [1]. Some physical properties are major dimensions (length, width and thickness), mass, GMD, sphericity and friction coefficients.

Friction coefficients of crops vary on different contact surfaces. Therefore, exact determination of friction coefficients of the crop on different contact surfaces can be useful in performance optimization of mechanical equipment (conveyors, separation, cleaning, drying and storing tools), and consequently, reduction and increment of harmful damages and economic efficiency, respectively [2].

Friction forces perform between two contact surfaces. Required force for initial movement of a motionless object depends on static friction force and the force for continuous movement of an object at a specific velocity relies on dynamic friction force. According to Brubaker and Pos [3], the relation between friction force and friction coefficient can be presented as following equation.

\[
FF = FC \times NF
\]  
(1)

According to Eq. (1), friction coefficient directly affects the friction force value. Therefore, researches about the effect of various conditions and treatments on friction coefficients are needed to gain information for controlling friction forces.

Friction coefficients include SFC and DFC with respect to static and dynamic friction forces, respectively. The SFC and DFC of crop depend on moisture content. Additionally, in case of DFC, the sliding velocity is also an important factor [2].

The frictional forces occur on a vertical plane in storage structures and handling equipment of wheat grain. On walls and floor of storage bins, frictional forces play an important role in discharging process in the plug flow region. The SFC and DFC, and consequently frictional forces, are influenced by the interaction of wheat grain particles and the surface of bin wall [4]. This interaction significantly affects the distribution and magnitude of loads applied on storage structures [5]. However, knowledge about the impact of many treatments on the SFC and DFC is still incomplete. Thus, additional experimental works are needed to determine the exact frictional behavior of wheat grain on different contact surfaces.

A review of published works confirmed that although the SFC of wheat grain has been studied by several previous investigators [3–23], there is no extended study for the determination of the effect of moisture content and contact surface on SFC of wheat grain. Neither, there are perfect attempts available in literature reporting the effect of moisture content, contact surface or sliding velocity on DFC of wheat grain [24–30]. Therefore, a comprehensive investigation of SFC and DFC for wheat grain taking several experimental conditions into considerations will be useful for optimization of storage and processing structures, especially grain bins.

In light of the above mentioned deficiencies and the benefits of knowing about SFC and DFC of wheat grain for optimization of related industry structures and equipment, the key scope of the present work on wheat grain was concentrated on following items:

1. Precise determination of SFC and DFC as effected by moisture content and contact surface, and moisture content, contact surface and sliding velocity, respectively.
2. To carry out statistical analysis to study the effect of moisture content, sliding velocity, contact surface and their DIE on DFC, and moisture content, contact surface and their DIE on SFC.
3. Comparing statistical significance of the effect of different treatment levels on SFC and DFC.
4. Assessment of predictive ability of MLR model for SFC and DFC based on multiple input variables (moisture content and sliding velocity) for each contact surface.

Material and methods

Grain collection

Shiroudi variety of wheat (Triticum aestivum L.), one of the most commonly used varieties in south region of Iran, was collected from Seed and Plant Breeding Unit, Agricultural Research Center of Fars province. Initially, the grains were cleaned by hand in order to remove undesired materials such as gravel, stone and injured seed.
grains. The prepared grains were then transferred to the research laboratory to determine physical properties.

**Physical properties**

One hundred wheat grains were randomly chosen to determine some physical properties. Three principal dimensions (length, width and thickness) of the grains were then measured with a digital caliper model: 01409A (Neiko, New Jersey, USA), reading to an accuracy of 0.02 (mm). The grains were weighed using a precision electronic balance model: GF-600 (A&D, Tokyo, Japan) with 0.001 (g) accuracy. Besides, some shape indices of the grains (GMD, sphericity and surface area) were calculated based on following equations [2].

\[
D_g = (LWT)^{1/3}
\]  \(2\)

\[
S = \left(\frac{D_g}{L}\right) \times 100
\]  \(3\)

\[
S_a = \pi (D_g)^2
\]  \(4\)

**Determination of initial moisture content**

A ten-gram sample of wheat grains was dried in a convection oven at 130 ± 1 (°C) for 19 (h). The initial moisture content of the grains was then determined as the mass reduction during drying procedure divided by dry mass of the grains [31]. To eliminate measurement error, the tests were completed in triplicate and mean value was used. The initial moisture content of wheat grain was 9.4% (d. b.).

**Sample preparation**

The grains were moistened to achieve a higher moisture content (13, 17.2, 20.9 and 25% (d. b.)) by attachment of specific quantity of distilled water calculated by following equation [32].

\[
W_w = W_i \frac{M_i - M_f}{100 - M_f}
\]  \(5\)

The hydrated samples were packed in separate polyethylene bags and placed in a refrigerator at 5 ± 0.5 (°C) for ten days to allow water be uniformly absorbed into grains [33]. The required quantity of samples was located at ambient condition to warm up to room temperature, almost two hours before starting each frictional experiment [34].

**Frictional experiments**

The SFC of samples was precisely measured on five contact surfaces (aluminum, rubber, glass, galvanized steel and plywood) at different levels of moisture content by means of a SFC measuring instrument. The instrument was initially proposed by Singh and Goswami [35] and improved mechanically and electrically by Lor estani et al. [36] and Shafaei et al. [23]. A schematic of the instrument is shown in details in Fig. 1a. Technical specifications and engineering aspects of the instrument are available in the literature.

The DFC of samples was also measured accurately on each type of contact surface at different levels of moisture content and sliding velocities (1, 3.5, 5.75, 9.25, and 12.5 (cm/s)) using a DFC measuring instrument. The higher sliding velocities were ignored in order to avoid probable damages to the samples. The instrument was originally suggested by Clark and Mcfarland [37] and developed and frequently used by other researchers, afterwards [4,38]. The instrument is schematically illustrated in Fig. 1b. The details of development and engineering considerations of the instrument are fully explained in the literature.

Before starting each experiment, the contact surface was cleaned by means of compressed air to eliminate any remaining matter from previous experiments. Each experiment was accomplished in five replications at constant normal pressure of 22.5 (kPa).

**Data analysis**

**Statistical descriptions**

To study changes in measured SFC and DFC of the samples as influenced by applied treatments, the statistical descriptor parameters, namely mean, standard deviation, coefficient of variation and coefficient of non-uniformity were used based on following equations.

\[
M = \frac{\sum_{i=1}^{N} FC_{act,i}}{N}
\]  \(6\)

\[
SD = \sqrt{\frac{\sum_{i=1}^{N} (FC_{act,i} - M)^2}{N}}
\]  \(7\)

\[
CV = \left(\frac{SD}{M}\right) \times 100
\]  \(8\)

\[
CNU = \left(\frac{FC_{max} - FC_{min}}{M}\right) \times 100
\]  \(9\)

**Statistical analysis**

The collected data (125 and 625 sets for SFC and DFC, respectively) were analyzed for sliding velocity (5 levels), moisture content (5 levels) and contact surface (5 types), each with five replications. For this purpose, the statistical analysis system of SPSS 21 software (SPSS Inc., Chicago, IL, USA) was used. The ANOVA

![Fig. 1. Schematic of the used SFC (a) and DFC (b) measuring instrument.](image-url)
method was applied to determine the effect of moisture content, contact surface and their DIE on SFC and also the effect of sliding velocity, contact surface and moisture content, and their DIE and TIE on DFC. The experiments were performed according to completely randomized factorial design with two and three main treatment factors for SFC and DFC, respectively, at 99% probability level. Contribution of each variation to SFC and DFC was then calculated based on the ANOVA results using Eq. (10). Differences between means of the treatments were also compared using DMRT at 1% significance level.

\[
C = \frac{SS_m}{SS_T} \times 100
\]  

(10)

Development of MLR models

The MLR models, based on Eq. (11), were developed for the means of data (25 and 125 sets for SFC and DFC, respectively) obtained from all five-replication experiments using SPSS 21 software (SPSS Inc., Chicago, IL, USA). The model was fed with one (moisture content) and two (moisture content and sliding velocity) input variables, respectively, for prediction of SFC and DFC on each contact surface. The significance of constants and coefficients of the developed models was also determined at 99% probability level.

\[
FC = a_0 + a_1x_1 + a_2x_2 + \cdots + a_nx_n + \varepsilon
\]  

(11)

In order to assess predictive ability of developed models, statistical parameters (coefficient of determination \(R^2\), RMSE and MRDM) were calculated between modeled and actual SFC or DFC according to following equations.

\[
R^2 = \frac{\sum_{i=1}^{N} (FC_{acti} - FC_{attave}) - \sum_{i=1}^{N} (FC_{acti} - FC_{modi})}{\sum_{i=1}^{N} (FC_{acti} - FC_{attave})}
\]  

(12)

\[
RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (FC_{modi} - FC_{acti})^2}
\]  

(13)

\[
MRDM = \frac{100}{N} \sum_{i=1}^{N} \left( \frac{FC_{modi} - FC_{acti}}{FC_{acti}} \right)
\]  

(14)

Results and discussion

Physical properties

The length, width, thickness, mass, GMD, surface area and sphericity of the wheat grain are presented in detail in Table 1.

| Physical property | Median | Range       | Geometric mean |
|-------------------|--------|-------------|----------------|
| Length (mm)       | 7.546  | 6.513–8.658 | 7.234          |
| Width (mm)        | 3.546  | 3.026–3.952 | 3.664          |
| Thickness (mm)    | 2.439  | 2.251–2.791 | 2.532          |
| Mass (g)          | 0.029  | 0.023–0.048 | 0.036          |
| GMD (mm)          | 3.955  | 3.356–4.236 | 4.087          |
| Surface area (mm²) | 48.658 | 47.921–51.650 | 49.126         |
| Sphericity (%)    | 65.867 | 57.398–69.425 | 64.345         |

Table 1

Statistical description of measured SFC and DFC of wheat grain.

| Type of friction coefficient | Mean | Standard deviation | Minimum | Maximum | CV (%) | CNU (%) |
|------------------------------|------|--------------------|---------|---------|--------|---------|
| SFC                          | 0.512| 0.121              | 0.240   | 0.693   | 23.63  | 88.48   |
| DFC                          | 0.467| 0.124              | 0.204   | 0.809   | 26.55  | 129.55  |

Table 2

Statistical analysis

Tables 3 and 4, respectively, present ANOVA results for SFC and DFC of wheat grain under different treatments. With reference to the Tables, it can be stated that the effect of treatments and interactions of them (DIE and TIE) on SFC and DFC were significant at 1% probability level \((P < 0.01)\). These effects on SFC and DFC are necessary engineering considerations that should be taken in designing crop handling equipment and storage structures to reach the best operation conditions.

The limited range of standard deviations verified high accuracy and stability of the measuring instruments.

Statistical descriptor parameters for measured SFC and DFC of wheat grain corresponding to five levels of moisture content and sliding velocity on different contact surfaces are reported in Table 2. According to Table 2, minimum and maximum SFC were obtained in the lowest and highest level of moisture content on glass and rubber, respectively. The inappropriate coefficient of variation and coefficient of non-uniformity for SFC implied that the SFC sharply changed by changing moisture content level or contact surface type.

Similar to SFC, the lowest and highest DFC were found in minimum and maximum levels of moisture content and sliding velocity on glass and rubber, respectively \((\text{Table 2})\). Improper coefficient of variation and coefficient of non-uniformity for DFC also indicated that the DFC changed sharply as influenced by variation of levels of moisture content, sliding velocity or contact surface type.

Comparison between coefficient of variation and coefficient of non-uniformity for the SFC and DFC in Table 2 demonstrated that the DFC-related values were higher than those of SFC. In case of DFC, three treatments were applied while, two treatments were applied to study SFC behavior. Therefore, the variation of DFC, and consequently the DFC-related values, were higher than those of SFC.

Effect of treatments

**Moisture content.** DMRT results of the effect of moisture content on SFC and DFC of wheat grain are reported in Table 5. It was inferred from the Table that the increment of moisture content from 9.4 to 25% (d. b.) led to SFC and DFC rise of 59 and 33.75%, respectively. As the moisture content increases, the grains become stickier and accordingly, cohesive force between grains and contact surface increases. The higher cohesive forces will result in the higher SFC \([39]\) and DFC \([40]\).
Sliding velocity

Table 5 indicates the increasing trend of DFC of wheat grain with ascending sliding velocity, according to the DMRT results. Based on the Table values, it can be concluded that increment of sliding velocity from 1 to 12.5 (cm/s) led to the notable change of DFC from the lowest to highest value by 33.5%. Higher adhesive force at higher sliding velocity might have resulted in the DFC growth [24].

Contact surface

The DMRT results demonstrated that contact surface significantly affected SFC and DFC of wheat grain (Table 5). The lowest SFC and DFC were found on the glass and aluminum contact surface, respectively. The SFC and DFC changed from lowest to highest value by 64% and 80.29%, respectively. It was due to the coarseness or smoothness of different contact surfaces. Smoother surface
DMRT results for the DIE of treatments on SFC of wheat grain.

Table 6

| Treatments | Contact surface | Moisture content (d. b.%) |
|------------|-----------------|--------------------------|
|            | 9.4             | 13                       | 17.2                     | 20.9                     | 25                       |
| Glass      | 0.240 ± 0.019<sup>a</sup> | 0.339 ± 0.017<sup>b</sup> | 0.356 ± 0.022<sup>c</sup> | 0.426 ± 0.010<sup>d</sup> | 0.516 ± 0.011<sup>e</sup> |
| Aluminum   | 0.320 ± 0.010<sup>a</sup> | 0.422 ± 0.009<sup>b</sup> | 0.440 ± 0.012<sup>c</sup> | 0.496 ± 0.019<sup>d</sup> | 0.537 ± 0.016<sup>e</sup> |
| Plywood    | 0.413 ± 0.004<sup>d</sup> | 0.469 ± 0.004<sup>d</sup> | 0.518 ± 0.009<sup>h</sup> | 0.585 ± 0.007<sup>i</sup> | 0.651 ± 0.007<sup>j</sup> |
| Galvanized Steel | 0.468 ± 0.017<sup>f</sup> | 0.548 ± 0.011<sup>i</sup> | 0.638 ± 0.015<sup>k</sup> | 0.655 ± 0.011<sup>l</sup> | 0.677 ± 0.008<sup>m</sup> |
| Rubber     | 0.495 ± 0.008<sup>b</sup> | 0.573 ± 0.009<sup>g</sup> | 0.651 ± 0.006<sup>m</sup> | 0.662 ± 0.009<sup>rn</sup> | 0.693 ± 0.009<sup>n</sup> |

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

The results indicated that moisture content increase from 9.4 to 25% (d. b.) along with the change from smooth contact surface to the coarse one (from glass to rubber) resulted in a 189% increment of SFC. In the Table, different letters represent a significant difference among SFCs at probability level of 1%. This significant DIE of moisture content and contact surface on SFC can be interpreted as the grain moisture content could be transferred to the contact surface and the moisturized contact surface acts as a contact surface with different characteristics and accordingly, the SFC vary. Hence, to achieve the same frictional behavior of wheat grain, each treatment combination with identical results on SFC is recommended for controlling SFC regarding available facilities.

DMRT results for the DIE of moisture content and contact surface on SFC of wheat grain are presented in Table 6. A precise analysis of the results indicated that moisture content increase from 9.4 to 25% (d. b.) along with the change from smooth contact surface to the coarse one (from glass to rubber) resulted in a 189% increment of SFC. In the Table, different letters represent a significant difference among SFCs at probability level of 1%. This significant DIE of moisture content and contact surface on SFC can be interpreted as the grain moisture content could be transferred to the contact surface and the moisturized contact surface acts as a contact surface with different characteristics and accordingly, the SFC vary. Hence, to achieve the same frictional behavior of wheat grain, each treatment combination with identical results on SFC is recommended for controlling SFC regarding available facilities.

Table 7 reports the DIE of applied treatments (moisture content, contact surface and sliding velocity) on the DFC of wheat grain on the basis of DMRT results. In the Table, different letters represent a significant difference among DFCs as affected by applied treatments at probability level of 1%. The significant DIE of moisture content and contact surface on DFC can be physically explained in a way similar to that of SFC. The significant DIE of moisture content and sliding velocity could be also related to changes in the temperature of contact surface. As the sliding velocity changes, the frictional energy also changes and releases in the form of heat. The grain moisture content changes as affected by the heat produced, and thereby, the DFC changes. In case of the significant DIE of contact surface and sliding velocity on DFC, it can be stated that the heat which is produced when sliding velocity changes might affect the structure of contact surface and, the DFC changes accordingly.

Regarding user point of view, to optimize the performance of corresponding equipment and structures, altering levels of the treatments with insignificant DIE on DFC in Table 7 is suggested. Analysis of data presented in Table 7 revealed that the DFC increased by 154.48% as a result of concurrent change of contact surface from glass to rubber and moisture content from 9.4 to 25% (d. b.). Besides, DFC increased 79.88% with simultaneous increment of moisture content and sliding velocity from 9.4 to 25% (d. b.) and from 1 to 12.5 (cm/s), respectively. It was also found that the change of contact surface from glass to rubber and sliding velocity from 1 to 12.5 (cm/s) resulted in an increase of DFC by 148.92%.

TIE Table 8 displays a comparison among mean DFC of wheat grain as affected by triple interaction of the treatments performed by DMRT. According to the Table, a 296.57% increment of DFC from the poor frictional condition (contact surface: glass, sliding veloc-
ity: 1 (cm/s) and moisture content: 9.4% (d. b.) to the strong frictional condition (contact surface: rubber, sliding velocity: 12.5 (cm/s) and moisture content: 25% (d. b.)) was observed. Different letters in the Table represent significant differences at probability level of 1%. The physical interpretation of this significant TIE on DFC can be mentioned by changes in sliding velocity, the released heat changes the grain moisture content and consequently contact surface structure differs and therefore, the DFC changes.

Table 8
DMRT results for the TIE of treatments on DFC of wheat grain.

| Contact surface | Moisture content (d. b.%) | Sliding velocity (cm/s) |
|-----------------|---------------------------|-------------------------|
| Glass           |                           | 1  | 3.5 | 5.75 | 9.25 | 12.5 |
| 9.4             | 0.204 ± 0.003^*           | 0.245 ± 0.009^a          | 0.294 ± 0.005^b         | 0.328 ± 0.005^m         | 0.379 ± 0.005^w         |
| 13              | 0.227 ± 0.007^de          | 0.276 ± 0.004^e          | 0.331 ± 0.006^f         | 0.368 ± 0.005^ik        | 0.405 ± 0.007^a         |
| 17.2            | 0.277 ± 0.005^de          | 0.316 ± 0.012^de         | 0.397 ± 0.012^f         | 0.421 ± 0.007^e         | 0.440 ± 0.010^e         |
| 20.9            | 0.319 ± 0.003^ef          | 0.388 ± 0.008^ef         | 0.414 ± 0.004^ef        | 0.482 ± 0.005^p         | 0.528 ± 0.007^z         |
| 25              | 0.364 ± 0.008^ef          | 0.415 ± 0.003^df         | 0.479 ± 0.006^df        | 0.523 ± 0.007^y         | 0.542 ± 0.008^z         |
| Aluminum        |                           | 9.4| 0.256 ± 0.005^cq         | 0.290 ± 0.005^cq        | 0.322 ± 0.005^e         | 0.352 ± 0.004^e         |
| 13              | 0.286 ± 0.003^ef          | 0.312 ± 0.003^f          | 0.327 ± 0.003^f         | 0.351 ± 0.001^h         | 0.373 ± 0.001^i         |
| 17.2            | 0.316 ± 0.002^ef          | 0.332 ± 0.001^f          | 0.355 ± 0.001^f         | 0.370 ± 0.001^f         | 0.383 ± 0.001^f         |
| 20.9            | 0.332 ± 0.001^ef          | 0.357 ± 0.001^f          | 0.377 ± 0.001^f         | 0.391 ± 0.001^f         | 0.406 ± 0.001^f         |
| 25              | 0.343 ± 0.001^ef          | 0.369 ± 0.001^f          | 0.392 ± 0.001^f         | 0.413 ± 0.006^c         | 0.432 ± 0.001^f         |
| Plywood         |                           | 9.4| 0.356 ± 0.004^op         | 0.376 ± 0.004^op        | 0.408 ± 0.004^op        | 0.442 ± 0.005^c         |
| 13              | 0.374 ± 0.003^ef          | 0.418 ± 0.005^ef         | 0.455 ± 0.002^ef        | 0.466 ± 0.002^ef        | 0.495 ± 0.002^ef        |
| 17.2            | 0.390 ± 0.004^ef          | 0.433 ± 0.003^ef         | 0.485 ± 0.004^ef        | 0.478 ± 0.003^ef        | 0.538 ± 0.003^ef        |
| 20.9            | 0.408 ± 0.003^ef          | 0.459 ± 0.003^ef         | 0.484 ± 0.002^ef        | 0.535 ± 0.006^ef        | 0.565 ± 0.003^ef        |
| 25              | 0.441 ± 0.005^ef          | 0.494 ± 0.002^ef         | 0.504 ± 0.003^ef        | 0.557 ± 0.003^ef        | 0.578 ± 0.002^ef        |
| Galvanized steel|                           | 9.4| 0.410 ± 0.004^be         | 0.430 ± 0.004^be        | 0.462 ± 0.004^be        | 0.496 ± 0.005^be        |
| 13              | 0.428 ± 0.003^ef          | 0.472 ± 0.005^ef         | 0.509 ± 0.002^ef        | 0.520 ± 0.002^ef        | 0.549 ± 0.002^ef        |
| 17.2            | 0.444 ± 0.002^ef          | 0.487 ± 0.003^ef         | 0.512 ± 0.004^ef        | 0.532 ± 0.003^ef        | 0.592 ± 0.005^ef        |
| 20.9            | 0.462 ± 0.003^ef          | 0.513 ± 0.003^ef         | 0.538 ± 0.002^ef        | 0.589 ± 0.006^ef        | 0.619 ± 0.003^ef        |
| 25              | 0.495 ± 0.005^ef          | 0.548 ± 0.002^ef         | 0.558 ± 0.003^ef        | 0.611 ± 0.003^ef        | 0.632 ± 0.002^ef        |
| Rubber          |                           | 9.4| 0.441 ± 0.005^ef          | 0.499 ± 0.005^ef        | 0.561 ± 0.006^ef        | 0.569 ± 0.006^ef        |
| 13              | 0.532 ± 0.012^Z±k         | 0.568 ± 0.005^Z±k        | 0.590 ± 0.011^Z±k       | 0.616 ± 0.009^Z±k       | 0.648 ± 0.010^Z±k       |
| 17.2            | 0.572 ± 0.005^Z±k         | 0.588 ± 0.003^Z±k        | 0.628 ± 0.010^Z±k       | 0.652 ± 0.014^Z±k       | 0.682 ± 0.005^Z±k       |
| 20.9            | 0.610 ± 0.048^Z±k         | 0.639 ± 0.004^Z±k        | 0.675 ± 0.015^Z±k       | 0.697 ± 0.021^Z±k       | 0.743 ± 0.005^Z±k       |
| 25              | 0.646 ± 0.005^Z±k         | 0.697 ± 0.006^Z±k        | 0.743 ± 0.014^Z±k       | 0.795 ± 0.004^Z±k       | 0.809 ± 0.002^Z±k       |

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

Fig. 3. Increment of SFC (a) and DFC (b) of wheat grain as affected by treatments.
To attain the best frictional condition based on engineering principles, the applied treatments resulted in the DFC with the same letters in the Table 8 can be considered as alternatives.

Comparison of the positive effect of treatments

**SFC**

Fig. 3a depicts the increment of SFC of wheat grain obtained from analysis of DMRT results versus applied treatments. It is clearly observed that the variation of SFC as affected by DIE of moisture content and contact surface has been greater (3 and 3.2 times) than that as influenced by SE of contact surface, succeeding by SE of moisture content. The more efficient SE of contact surface than SE of moisture content (1.1 times) was in agreement with the prediction addressed in the Statistical Analysis Section. Therefore, to control the SFC of wheat grain, applying simultaneous changes in moisture content and contact surface rather than individual change of contact surface or moisture content, is suggested as a more effective way.

**DFC**

Fig. 3b shows a chart comparing the effect of different treatments on the increment of DFC of wheat grain. As it can be seen in the Fig., TIE of the treatments was more efficient (2, 3.7, and 2 times) than DIE, followed by SE of treatments (8.8, 3.7 and 8.9 times). The greater SE of contact surface (2.4 times) than SE of moisture content or sliding velocity was also predicted by the results of contribution of variation presented in the Statistical Analysis Section. Application of these results is suggested to be considered for decrement or increment of DFC of wheat grain in respective equipment and structures.

Evaluation of developed MLR models

The constants, coefficients and statistical parameters of MLR models developed for prediction of SFC and DFC of wheat grain regarding to each contact surface are listed in Table 9. The acceptable values of coefficient of determination ($R^2 > 0.9$), RMSE and MRDM tabulated in the Table confirmed that the SFC and DFC of

| Contact surface | Type of friction coefficient | $a_0$ | $a_1$ | $a_2$ | $R^2$ | RMSE | MRDM (%) |
|-----------------|-----------------------------|-------|-------|-------|-------|-------|----------|
| Glass           | SFC                         | 0.0967| 0.0163| 0      | 0.959 | 0.02405| 4.795    |
|                 | DFC                         | 0.0756| 0.0116| 0.0157| 0.972 | 0.01651| 3.512    |
| Aluminum        | SFC                         | 0.2220| 0.0129| 0      | 0.939 | 0.02362| 3.634    |
|                 | DFC                         | 0.2143| 0.0053| 0.0070| 0.975 | 0.00699| 1.508    |
| Plywood         | SFC                         | 0.2682| 0.0152| 0      | 0.996 | 0.00717| 0.842    |
|                 | DFC                         | 0.2772| 0.0066| 0.0113| 0.966 | 0.01174| 1.898    |
| Galvanized steel| SFC                         | 0.3679| 0.0134| 0      | 0.902 | 0.03159| 3.538    |
|                 | DFC                         | 0.3312| 0.0066| 0.0113| 0.963 | 0.01174| 1.696    |
| Rubber          | SFC                         | 0.4030| 0.0124| 0      | 0.911 | 0.02760| 2.944    |
|                 | DFC                         | 0.3407| 0.0128| 0.0113| 0.962 | 0.01777| 2.152    |
wheat grain were appropriately predicted by MLR model in moisture content range of 9.4 to 25% (d. b.) and sliding velocity range of 1 to 12.5 (cm/s) on galvanized steel, glass, aluminum, rubber and plywood contact surfaces. It was also found that the constant and coefficient obtained for each developed MLR model documented in the Table were significant at 99% probability level.
Comparison of the SFC and DFC of wheat grain results obtained in the present study with other published researches.

| Contact surface | Type of friction coefficient | Measured range | Predicted range by the model | Reported range in literature | Authors |
|-----------------|-------------------------------|----------------|-----------------------------|--------------------------------|---------|
| Glass           | SFC                           | 0.240–0.516    | 0.250–0.504                 | 0.279–0.401                    | Tabatabaeefar [13] |
|                 | DFC                           | 0.204–0.542    | 0.200–0.562                 | –                              | –       |
| Aluminum        | SFC                           | 0.320–0.537    | 0.343–0.545                 | 0.210–0.260                    | Zhang et al. [5] |
|                 | DFC                           | 0.256–0.432    | 0.271–0.435                 | –                              | –       |
| Plywood         | SFC                           | 0.413–0.651    | 0.411–0.647                 | 0.458–0.498                    | Zaalouk and Zabady [16] |
|                 | DFC                           | 0.356–0.578    | 0.351–0.584                 | –                              | –       |
| Galvanized steel| SFC                           | 0.468–0.677    | 0.494–0.703                 | 0.232–0.713                    | Kaliniewicz [17] |
|                 | DFC                           | 0.410–0.632    | 0.405–0.638                 | 0.163–0.203                    | Molenda et al. [28] |
| Rubber          | SFC                           | 0.495–0.693    | 0.520–0.713                 | 0.496–0.605                    | Zaalouk and Zabady [16] |
|                 | DFC                           | 0.441–0.809    | 0.472–0.801                 | 0.510–0.875                    | Sharobeen [29] |

The above mentioned conclusions are valuable practical points to optimize storage equipment and processing conditions such as grain bins. The analysis method used in this paper, based on ANOVA and DMRT, is recommended to be applied in investigation of the effect of influential treatments on SFC and DFC of other important major crops.
Conflict of Interest

The authors have declared no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

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