Bulgarian Journal of Agricultural Science, 30 (No 5) 2024, 921–929

Losses from leakage of grain and seeds through openings in machinery and equipment

Miroslav Mihaylov* **and Bozhidar Kolev**

University of Ruse "Angel Kanchev"
**Corresponding author:* mmihaylov@uni-ruse.bg

Abstract

Mihaylov, M. & Kolev, B. (2024). Losses from leakage of grain and seeds through openings in machinery and equipment. *Bulg. J. Agric. Sci., 30*(5), 921–929

In the period of processing and storage of grain production, losses due to leakage of grain are observed during its movement between machines and installations and during storage in bunkers and silos. Scattering is mainly the result of leakage of grain and seeds through cracks, crevices, holes in machinery and equipment. Losses from the leakage of grain and seeds through openings of different shapes and sizes have been investigated. Boundary dimensions of openings of different shape and size have been defined, through which the flow of grain and seeds from various crops is stopped. Mathematical models of the rate of grain and seeds losses due to leakage through different openings have been obtained. The adequacy of the models for practice have been evaluated.

*Keywords***:** grain and seeds; postharvest handling; leakage losses; flow rate

Introduction

Grain loss is a problem for all agricultural production in the world (Nagpal & Kumar, 2012; Schulten, 1982). The losses directly or indirectly affect the cost of production, the final market price, the satisfaction of people's needs and lead to environmental pollution (Balai et al., 2018; Gustavsson et al., 2011).

According to the causes of the losses, the latter are divided into those of an objective nature, caused by climatic problems and the ones of a subjective nature, depending on the actions and/or inactions of man.

Losses of a subjective nature occur during harvesting, transportation, processing and storage (Grover et al., 2012; Seth et al., 2018; Kumar & Kalita, 2017). Grain losses, mostly at harvest time, have been studied and investigated (Bratoev et al., 2013; Glancey, 1997; Kringe & Newman, 2022; Patel & Varshney, 2014; Rod et al., 2013), as well as losses caused by diseases and pests during storage (Boxall, 2001 and 2002; De Groote et al., 2013).

In the post-harvest processing period and during grain and seed storage, losses of a different nature occur. Part of them are the losses from leakage of grain (seeds) through openings in the equipment during the operation of the processing installations, during inter-machine transport, as well as in case of damage of a different nature to the storage capacities for grain of any kind. They are a consequence of: oxidation of metal surfaces (rust); material fatigue; missing rivets, bolts and nuts; mechanical damage to the integrity of external surfaces in case of accidental incidents or incorrect actions. Damages can be classified as cracks, crevices, punctures of different shapes and dimensions (width and length, or diameter). Grain leaks through them, which in general, is irretrievably lost.

The permissible losses of grain (Ordinance No. 13a-10403, 2007) during road and rail transport in Bulgaria are up to 0,14% of the total volume when transported in bulk and up to 0,10% of the total volume when transported in closed containers.

Allowable losses during storage in silos are:

- up to 0.12 % for beans and peas;
- up to 0.16% for wheat, rye and soy;
- up to 0.18% for barley, oats, spelt, millet and sorghum;
- up to 0.20% for rapeseed and grain corn.

The subject of the research is the loss of grain in the period of processing and storage, as a result of leaks from openings in the construction of processing machines, silos, bunkers, redlers and elevators. Losses of grain from diseases, pests and improperly selected storage modes are excluded.

Material and Methods

Different stages with variable velocities and flow rates are observed in the flow of grain from hoppers by applying empirical formulas based on the basic fluid flow equation (Srivastava et al., 1993; Moysey et al., 1988):

$$Q_m = f(F, H), \quad (1)$$

where Q is the mass flow rate, kg/h;

F is the clear section of the outlet hole, m^2;

H is the thickness of the grain layer, m.

In order to assess the possible losses from scattering of grain and seeds in the period of processing and storage, their leakage through holes of different shapes and sizes have been studied. In practice, this leakage is actually observed without changing the thickness of the layer or the height of the mound of grain (seeds). Therefore, we can expect a linear dependence of the mass flow rate Q_m, hereafter referred to as leakage losses, as a function of the orifice cross-section F according to the expression:

$$Q_m = f(F) \quad (2)$$

Grain and seeds of different shapes, sizes and roughness were selected for the experiments. The research was carried out with varieties and hybrids used in our country: wheat variety «Milena» and sunflower hybrid «Dalena» (from Dobruja Agricultural Institute – General Toshevo); corn hybrid «Knezha 435» (from the Institute of Maize – Knezha); sorghum hybrid ‘Lupus’; millet variety ‘Olitan’; bean variety «Plovdiv 15M».

The main characteristics of the grain and seeds of different crops (Kolev & Mihaylov, 2024) used in the research are presented in Table 1.

The studied grain and seeds of the above crops have admissible humidity for storage and content of impurities (EN ISO 24333, 2010). All tests were carried out in laboratory conditions at an ambient temperature of 15...20°C, and relative humidity 43...50%.

A stand (Fig. 1) allowing the change of the aperture 4 with different shapes and sizes of holes through which grain and seeds flow out, was used to imitate the cracks, slits, and ruptures that appeared in machines and equipment. The possible shapes are classified as circular and rectangular openings. The maximum light cross-section of the rectangular aperture has an area of 1600 mm^2, the length of the opening a is constant and is equal to 40 mm, and the width b of the rectangular cross-section can be changed smoothly from 1 to 40 mm. The round holes of the apertures have an area of < 800 mm^2.

In the case of round holes, it is possible to choose those with different diameters ($1 \leq Ø < 30$ mm). Given the above, instead of section F of the light opening through, which grain (seed) flows, we will use a characteristic size of a given type of opening – diameter of the round opening Ø and width of the rectangular opening b (at a constant length a). Thus, the required dependence for leakage through a round hole will be of the type:

$$Q_m = f(Ø), \quad (3)$$

and for outflow through a rectangular opening of the type:

$$Q_m = f(b) \quad (4)$$

Experiments have been performed in triplicate. For each repetition of a given experiment, a certain volume U_{0i}, ml of the corresponding grain (seeds) is poured into the hopper 1 (see Fig. 1).

Table 1. Physical and Mechanical Characteristics of Grain and Seeds

Type of culture	Form	Size		Roughness	Hecto-liter mass, kg/hl	Natural slope angle α, deg	Coeff. of friction on metal f
		mm	Classification				
Wheat	oblong	6.7×3.6×2.9	average	grooved	78.0	28	0.29
Corn	irregularly shaped	10.3×7.7×5.0	large	grooved	72.9	26	0.27
Sorghum	rounded	Ø 3.3	small	smooth	72.0	27	0.26
Millet	rounded	Ø 1.7	small	grooved	78.6	26	0.27
Sunflower	oblong	11.7×5.5×3.4	large	smooth	38.0	27	0.34
Beans	irregularly shaped	10.2×6.8×4.5	large	smooth	65.4	25	0.26

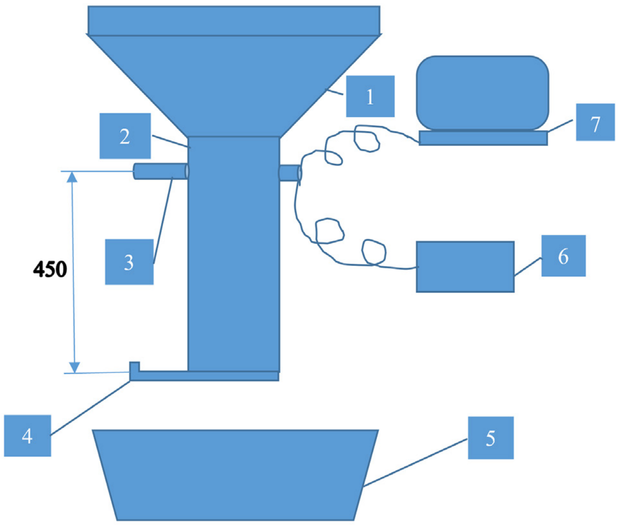

Fig. 1. Stand for studying the leakage of grain through different openings
1 – bunker; *2* – gravity pipe; *3* – sensor; *4* – aperture; *5* – collecting vessel; *6* – power supply unit; *7* – computer
The *Statistica 13* software programme for *Windows* was used to process the results.

The experiment begins with the opening of the shutter 4, as the sensor 3 sends a signal to start the electronic stopwatch of the developed device (Mihaylov & Georgieva, 1995). After passing the last grain (seed) through the beam of the sensor, the stopwatch is turned off. The grains (seeds) flow into a collection vessel 5. The corresponding volume U_i of the quantity flown into the vessel is calculated according to expression (5):

$$U_i = U_{0i} - U_C, \quad (5)$$

where U_i is the volume of leaked grain (seeds) for a given crop *i*, ml;
U_{0i} – the initial volume of grain (seeds) in the hopper, ml;
U_C – the constant volume locked between the sensor and the aperture, $U_C = 1260$ ml.

For each trial, the time value t_{ijk} is recorded and t_{ijsr} is calculated using the expression:

$$t_{ijcp} = \frac{1}{3}\sum_1^k t_{ijk}, \quad (6)$$

where t_{ijk} is the time for the grain to flow from the i^{th} type of crop through the j^{th} aperture during the k^{th} iterancy, s;
t_{ijcp} – the average value of the time for the grain to flow, s.

Next is the calculation of the flow rate Q_{ij} of the leaked grain (seeds) and the mass flow rate (losses) Q_{mij} according to expressions (7) and (8):

$$Q_{ij} = 3.6U_i/t_{ijcp}, \quad (7)$$

$$Q_{mij} = 10^{-2}HM_iQ_{ij}, \quad (8)$$

where Q_{ij} is the flow rate of the leaked grain (seeds) from the *i*-th type of crop through the j^{th} aperture, l/h;
Q_{mij} – losses (mass flow rate) of leaked grain (seeds) from the i^{th} type of crop through the j^{th} aperture, kg/h;
HM_i – the hectoliter mass of the i^{th} type of crop, kg/hl.

Results and analysis

Through preliminary laboratory tests, border shapes and sizes of holes were determined, through which no grain can flow in a layer no more than 450 mm thick. The results are systematized in Table 2. In cases of grain (seed) layer thickness over 450 mm at the quoted limit dimensions, no continuous flow of grain (seed) is observed even when transverse vibrations are excited along the gravity tube 2 (see Fig. 1) with different frequency and amplitude. It is known from practice that round-shaped holes through which grain (seeds) flow out are most likely to appear after rivets, screws and bolts of storage and transport equipment fall out. The maximum diameters of fasteners used do not exceed Ø25 mm. From the preliminary studies, it was found that leakage through an opening with a diameter of Ø25 mm of grain (seeds) of corn, sunflower and beans with a layer thickness of more than 450 mm is not observed.

Experimental data from studies of leakage (losses) Q_{mij} of wheat, sorghum and millet through round holes are presented in Table 3.

Fig. 2 presents the graphical images of the regression lines, the confidence regions for the predicted (calculated) values of leakage losses Q_{mij} of wheat, sorghum and millet through round holes, as well as the experimental values. The regression lines run very close to or through the exper-

Table 2. Results for boundary shapes and hole sizes, through which no grain flows

Type of crop	Boundary shapes	Border size, mm
Wheat	rectangular narrow	≤5 × 40
	round	≤ Ø16
Corn	rectangular wide	≤14 × 40
Sorghum	rectangular narrow	<2 × 40
	round	≤ Ø9
Millet	rectangular narrow	<2 × 40
	round	≤ Ø7
Sunflower	rectangular wide	≤14 × 40
Beans	rectangular wide	≤17 × 40

Table 3. Experimental data from the studies of leakage (losses) of grain and seeds through round holes

Diameter Ø, mm	Section *F*, mm^2	Duration t_{ijk}, s				Volume	Flow	Hectoliter mass HM_i	Mass flow rate (losses)
		1	2	3	t_{ijcp}, s	U_i, ml	Q_{ij}, l/h	kg/100 l	Q_{mij}, kg/h
WHEAT									
17	226.865	52.3	53.1	52.0	52.5	950	65.18	78.00	50.84
19	283.385	32.6	32.8	31.6	32.3	950	105.77	78.00	82.50
21	346.185	22.7	22.8	22.9	22.8	950	150.00	78.00	117.00
23	415.265	17.8	17.7	17.0	17.5	950	195.43	78.00	152.43
25	490.625	14.1	14.2	13.9	14.1	950	243.13	78.00	189.64
SORGHUM									
10	78.5	84.4	82.8	84.0	83.7	680	29.24	72.00	21.05
12	113.04	49.6	49.7	48.5	49.3	680	49.69	72.00	35.78
14	153.86	29.5	29.2	29.3	29.3	680	83.45	72.00	60.09
16	200.96	22.2	22.8	22.5	22.5	680	108.80	72.00	78.34
18	254.34	16.7	17.1	17.2	17.0	680	144.00	72.00	103.68
MILLET									
8	50.24	207.1	209.8	207.3	208.1	900	15.57	78.60	12.24
10	78.5	107.2	104.3	106.6	106.0	900	30.56	78.60	24.02
12	113.04	65.6	65.8	67.9	66.4	900	48.77	78.60	38.33
14	153.86	48.1	48.2	47.1	47.8	900	67.78	78.60	53.28
16	200.96	36.9	37.3	37.4	37.2	900	87.10	78.60	68.46

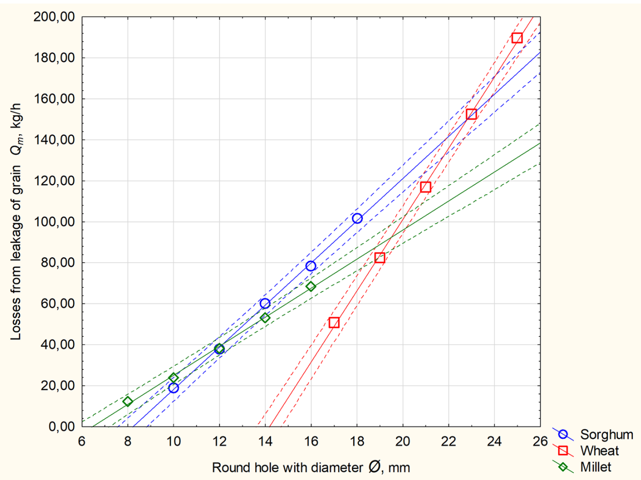

Fig. 2. Regression lines and confidence regions for the calculated values of grain leakage through a round hole

imental values, and the confidence regions (at confidence probability γ = 0,95) include all the experimental values.

The results of the regression analysis (Fig. 3) indicate that the coefficients of determination R^2 (for sorghum R^2 = 0.9934 or 99.34%; for wheat R^2 = 0.9991 or 99.91%; for millet R^2 = 0.9978 or 99.78%) are close to the value of one and indicate that their respective percentage of the leakage loss variation is due to the orifice diameter factor Ø. This variation is described by linear models. The regression coefficients of the linear models are significant. Fisher's criteria *F* and their corresponding probabilities *p* (see Fig. 3), show that the linear models (9), (10) and (11) can be considered adequate for the studied areas.

$$Q_{m\ \mathrm{sorghum}} = -85.686 + 10.391 \times Ø; \qquad (9)$$

$$Q_{m\ \mathrm{wheat}} = -246.424 + 17.377 \times Ø; \qquad (10)$$

$$Q_{m\ \mathrm{millet}} = -45.754 + 7.085 \times Ø. \qquad (11)$$

Table 4 presents the experimental data from the studies of leakage (losses) Q_{mij} of wheat, sorghum and millet through rectangular openings of constant length *a* and variable width *b*.

Fig. 4 shows the regression lines, experimental values and confidence regions for the predicted (calculated) values of leakage losses Q_{mij} of wheat, sorghum and millet through a rectangular opening of constant length *a* = 40 mm and variable width *b*. Within the confidence regions (at confidence probability γ = 0,95) fall all experimental values, and the regression lines pass immediately by, or

Regression Summary for Dependent Variable: $Q_{m\ \mathrm{wheat}}$ (Spreadsheet2 in Workbook1)
R= ,99956318 R?= ,99912656 Adjusted R?= ,99883541
F(1,3)=3431,7 p<,00001 Std.Error of estimate: 1,8760

N=5	b*	Std.Err. of b*	b	Std.Err. of b	t(3)	p-value
Intercept			-246,424	6,285378	-39,2060	0,000037
Ø, mm	0,999563	0,017063	17,377	0,296625	58,5806	0,000011

a

Regression Summary for Dependent Variable: $Q_{m\ \mathrm{sorghum}}$ (Spreadsheet2 in Workbook1)
R= ,99667358 R?= ,99335823 Adjusted R?= ,99114431
F(1,3)=448,69 p<,00023 Std.Error of estimate: 3,1025

N=5	b*	Std.Err. of b*	b	Std.Err. of b	t(3)	p-value
Intercept			-85,6860	7,006495	-12,2295	0,001177
Ø, mm	0,996674	0,047052	10,3910	0,490553	21,1822	0,000230

b

Regression Summary for Dependent Variable: $Q_{m\ \mathrm{millet}}$ (Spreadsheet2 in Workbook1)
R= ,99887780 R?= ,99775685 Adjusted R?= ,99700913
F(1,3)=1334,4 p<,00005 Std.Error of estimate: 1,2267

N=5	b*	Std.Err. of b*	b	Std.Err. of b	t(3)	p-value
Intercept			-45,7540	2,391210	-19,1342	0,000312
Ø, mm	0,998878	0,027344	7,0850	0,193953	36,5295	0,000045

c

Fig. 3. Regression analysis results for the linear models of leakage losses Q_m through round holes of:
a – wheat;
b – sorghum;
c – millet

Table 4. Experimental data from studies of grain and seed leakage through rectangular openings

Opening width b, mm	Section $F=40 \times b$, mm^2	Duration t_{ijk}, s				Volume	Flow	Hectoliter mass HM_i	Mass flow rate (losses)
		1	2	3	t_{ijcp}, s	U_i, ml	Q_{ij}, l/h	kg/100 l	Q_{mij}, kg/h
WHEAT									
6	240	35.4	35.7	35.5	35.5	950	96.25	78.00	75.07
7	280	22.9	22.3	22.4	22.5	950	151.78	78.00	118.38
8	320	16.2	16.1	16.2	16.2	950	211.55	78.00	165.01
9	360	12.8	12.6	12.6	12.7	950	270.00	78.00	210.60
10	400	9.7	10.4	10.1	10.1	950	339.74	78.00	264.99
SORGHUM									
2	80	65.9	62.4	62.6	63.6	680	38.47	72.00	27.70
3	120	33.8	34.7	30	32.8	680	74.56	72.00	53.68
4	160	19.9	22.8	21	21.2	680	115.29	72.00	83.01
5	200	15.1	15.1	15.1	15.1	680	162.12	72.00	116.73
6	240	11.8	12	11.9	11.9	680	205.71	72.00	148.11
MILLET									
2	80	98.1	97.8	98.8	98.2	900	32.98	78.60	25.92
3	120	41.6	42.9	40.8	41.8	900	77.57	78.60	60.97
4	160	25.4	25.7	25.5	25.5	900	126.89	78.60	99.74
5	200	18.4	16.9	17.0	17.4	900	185.85	78.60	146.08
6	240	13.5	13.2	13.3	13.3	900	243.00	78.60	191.00

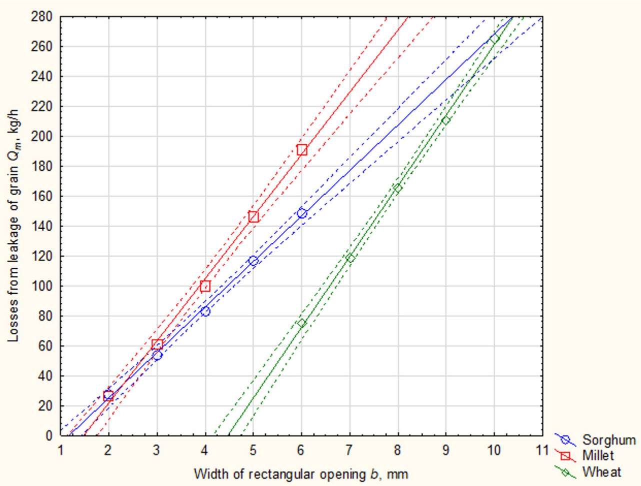

Fig. 4. Regression lines and confidence regions for the calculated values of losses, when grain flows through a rectangular opening with a section of 40 × *b*

through the points of the experimental values of leakage losses Q_{mij}.

The results of the regression analysis (Fig. 5) indicate that the coefficients of determination R^2 (for sorghum $R^2 = 0.9978$ or 99.78%; for millet $R^2 = 0.9967$ or 99.67%; for wheat $R^2 = 0.9983$ or 99.83%) are close to the value of one and indicate that their respective percentage of the leakage loss variation is due to the rectangular aperture width factor *b*. This variation is described by linear models. The regression coefficients of the linear models were significant. Fisher's criteria *F* and their corresponding probabilities *p* (see Fig. 5), show that the linear models (12), (13) and (14) can be considered adequate for the studied areas.

$$Q_{m\ \text{wheat}} = -210.838 + 47.206 \times b; \quad (12)$$

$$Q_{m\ \text{sorghum}} = -35.702 + 30.387 \times b; \quad (13)$$

$$Q_{m\ \text{millet}} = -61.306 + 41.507 \times b. \quad (14)$$

Table 5 presents the experimental data from the studies of leakage (losses) Q_{mij} of corn, sunflower and beans through rectangular openings of constant length a and variable width *b*.

Fig. 6 shows the regression lines, the experimental values and the confidence regions for the predicted (calculated) values of leakage losses Q_{mij} of corn, sunflower and beans through a rectangular opening with constant length

Table 5. Experimental data from studies of grain and seed leakage through rectangular openings

Opening width b, mm	Section $F = 40 \times b$, mm^2	Duration t_{ijk}, s				Volume	Flow	Hectoliter mass HM_i	Mass flow rate (losses)
		1	2	3	t_{ijcp}, s	U_i, ml	Q_{ij}, l/h	kg/100 l	Q_{mij}, kg/h
CORN									
15	600	13.1	12.8	12.8	12.9	1289	359.72	72.90	262.24
17,5	700	8.7	8.9	8.7	8.8	1289	527.32	72.90	384.41
20	800	5.7	5.8	5.3	5.6	1289	828.64	72.90	604.08
22,5	900	4.6	4.5	4.5	4.5	1289	1031.20	72.90	751.74
25	1000	3.6	3.5	3.6	3.6	1289	1301.05	72.90	948.46
SUNFLOWER									
15	600	7	7.2	7.2	7.1	740	373.46	38.00	141.91
17,5	700	4.9	4.3	5.1	4.8	740	558.88	38.00	212.37
20	800	3.1	3	3.5	3.2	740	832.50	38.00	316.35
22,5	900	2.3	2.6	2.5	2.5	740	1080.00	38.00	410.40
25	1000	1.9	2	1.9	1.9	740	1377.93	38.00	523.61
BEANS									
17,5	700	4.1	4.5	4.3	4.3	535	447.91	65.40	292.93
20	800	2.9	3.1	3.2	3.1	535	628.04	65.40	410.74
22,5	900	2.5	2.4	2.4	2.4	535	791.51	65.40	517.65
25	1000	1.9	1.9	2.1	2.0	535	979.32	65.4	640.48
27,5	1100	1.6	1.7	1.5	1.6	535	1203.75	65.4	787.25

N=5	Regression Summary for Dependent Variable: $Q_{m\ wheat}$ (Spreadsheet9 in Workbook2) R= ,99915418 R?= ,99830907 Adjusted R?= ,99774543 F(1,3)=1771,2 p<,00003 Std.Error of estimate: 3,5470					
	b*	Std.Err. of b*	b	Std.Err. of b	t(3)	p-value
Intercept			-210,838	9,112530	-23,1372	0,000177
b, mm	0,999154	0,023741	47,206	1,121675	42,0853	0,000030

a

N=5	Regression Summary for Dependent Variable: $Q_{m\ sorghum}$ (Spreadsheet9 in Workbook2) R= ,99888740 R?= ,99777603 Adjusted R?= ,99703471 F(1,3)=1345,9 p<,00004 Std.Error of estimate: 2,6192					
	b*	Std.Err. of b*	b	Std.Err. of b	t(3)	p-value
Intercept			-35,7020	3,514077	-10,1597	0,002032
b, mm	0,998887	0,027227	30,3870	0,828276	36,6870	0,000045

b

N=5	Regression Summary for Dependent Variable: $Q_{m\ millet}$ (Spreadsheet9 in Workbook2) R= ,99833152 R?= ,99666582 Adjusted R?= ,99555443 F(1,3)=896,77 p<,00008 Std.Error of estimate: 4,3831					
	b*	Std.Err. of b*	b	Std.Err. of b	t(3)	p-value
Intercept			-61,3060	5,880530	-10,4253	0,001884
b, mm	0,998332	0,033338	41,5070	1,386054	29,9462	0,000082

c

Fig. 5. Regression analysis results for the linear models of leakage losses Q_m through rectangular openings of:
a – wheat;
b – sorghum;
c – millet

a = 40 mm and variable width b. Within the confidence regions (at confidence probability γ = 0,95) fall all experimental values, and the regression lines pass immediately by or through the points of the experimental values of leakage losses Q_{mij}.

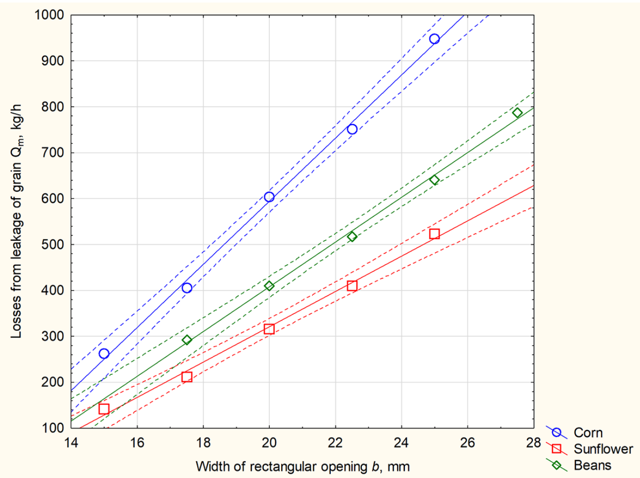

Fig. 6. Regression lines and confidence regions for the calculated values of losses when grain flows through a rectangular opening with a section of 40 × *b*

The results of the regression analysis (Fig. 7) indicate that the coefficients of determination R^2 (for corn R^2 = 0.9972 or 99.72%; for sunflower R^2 = 0.9946 or 99.46%; for beans R^2 = 0.9965 or 99.65%) are close to the value of one and indicate that their respective percentage of the leakage loss variation is due to the rectangular aperture width factor b. This variation is described by linear models. The regression coefficients of the linear models were significant. Fisher's criteria F and their corresponding probabilities p (see Fig. 7), show that the linear models (15), (16) and (17) can be considered adequate for the studied areas.

$$Q_{m\ corn} = -780.540 + 68.747 \times b; \quad (15)$$

$$Q_{m\ sunflower} = -448.216 + 38.457 \times b; \quad (16)$$

$$Q_{m\ beans} = -566.732 + 48.735 \times b. \quad (17)$$

Conclusions

The impossibility of grain (seeds) leaking from certain crops through holes of a certain shape and with dimensions below certain values at a height of the grain mound > 450 mm has been proven theoretically and confirmed experimentally.

N=5	Regression Summary for Dependent Variable: $Q_{m\ corn}$ (Spreadsheet9 in Workbook2) R= ,99858884 R?= ,99717967 Adjusted R?= ,99623956 F(1,3)=1060,7 p<,00006 Std.Error of estimate: 16,688					
	b*	Std.Err. of b*	b	Std.Err. of b	t(3)	p-value
Intercept			-780,540	42,87160	-18,2065	0,000361
b, mm	0,998589	0,030661	68,747	2,11085	32,5685	0,000064

a

N=5	Regression Summary for Dependent Variable: $Q_{m\ sunflower}$ (Spreadsheet9 in Workbook2) R= ,99728641 R?= ,99458019 Adjusted R?= ,99277358 F(1,3)=550,52 p<,00017 Std.Error of estimate: 12,958					
	b*	Std.Err. of b*	b	Std.Err. of b	t(3)	p-value
Intercept			-448,216	33,28904	-13,4644	0,000886
b, mm	0,997286	0,042504	38,457	1,63904	23,4633	0,000170

b

N=5	Regression Summary for Dependent Variable: $Q_{m\ beans}$ (Spreadsheet9 in Workbook2) R= ,99826689 R?= ,99653678 Adjusted R?= ,99538237 F(1,3)=863,24 p<,00009 Std.Error of estimate: 13,113					
	b*	Std.Err. of b*	b	Std.Err. of b	t(3)	p-value
Intercept			-566,732	37,77938	-15,0011	0,000643
b, mm	0,998267	0,033977	48,735	1,65873	29,3810	0,000087

c

Fig. 7. Regression analysis results for the linear models of leakage losses Q_m through rectangular openings of:
a – corn;
b – sunflower;
c – beans

The above is due to the increased frictional force between the particles due to the increased pressure in the mound caused by the normal pressure (weight) of the grain layer.

Adequate mathematical models have been obtained for leakage losses Q_m of grain and seeds of various crops through openings of various shape and size.

The resulting models allow the prediction and/or calculation of losses of grain and seeds during leakage through openings of characteristic shape and size in machinery and equipment.

References

Balai, H., Rathore, V., Jain, S. K. & Singh, H. (2018). Estimation of post-harvest losses of wheat in Indore (M.P.) India. *Journal of Pharmacognosy and Phytochemistry*, *7*(3), 2588-2592.

Boxall, R. A. (2001). Post-harvest losses to insects—A world review. *Int. Biodeterior. Biodegrad*, *48*, 137–152.

Boxall, R. (2002). Damage and loss caused by the larger grain borer. *Prostephanus truncatus*. *Integr. Pest Manag. Rev*, *7*, 105–121.

Bratoev, K., Demirev, Z. & Dobrinov, V. (2013). Preconditions for reduction of grain losses during the oil seed rape harvesting. *Mechanization in Agriculture*, 2, 7-10.

De Groote, H., Kimenju, S. C., Likhayo, P., Kanampiu, F., Tefera, T. & Hellin, J. (2013). Effectiveness of hermetic systems in controlling maize storage pests in Kenya. *J. Stored Prod. Res.*, 53, 27–36.

EN ISO 24333:2010. Cereals and cereal products.

Glancey, J. L. (1997). Analysis of header loss from pod stripper combines in green peas. *Journal of Agricultural Engineering Research*, *68*(1), 1-10.

Grover, D. K., Singh, J. M. & Singh, P. (2012). Assessment of Pre and Post Harvest Losses in Wheat and Paddy Crops in Punjab. *AERC STUDY,* No. 31, Punjab Agricultural University, Ludhiana, 102.

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R. & Meybeck, A. (2011). *Global Food Losses and Food Waste*; Food and Agriculture Organization of the United Nations: Rome, Italy

Kolev, B. R. & Mihaylov M. D. (2024). Physical and Mechanical Characteristics of Grain and Seeds. *Bulgarian Journal of Agricultural Science*, *30*(1), 96-100.

Kringe, M. & Newman, P. (2022). Harvest loss goals as grain percentage. Available at: https://grdc.com.au/resources-and-publications/resources/harvest-resources/harvest-loss. Last accessed: 11.08.2022.

Kumar, D. & Kalita, P. (2017). Reducing Postharvest Losses during Storage of Grain Crops to Strengthen Food Security in Developing Countries. *Foods, 6*(1), 8. Available at: https://doi.org/10.3390/foods6010008. Last accessed: 31.07.2022.

Mihaylov, M. & Georgieva, K. (1995). System for control of seed inflow in sub-layered sowing machines. *Proceedings of the Jubilee Scientific Conference of the Higher Institute of Yambol*. Bulgaria, 6-7 April 1995, 65-69 (Bg).

Moysey, E. B., Lambert, E. W. & Wang, Z. (1988). Flow rates of grains and oilseedsthrough sharp-edged orifices. Transactions of the *ASAE, 31*(1), 226:231.

Nagpal, M. & Kumar, A. (2012). Grain losses in India and government policies. *Qual. Assur. Saf. Crops Foods*, *4*, 143.

Ordinance №13a-10403 of the Government of Bulgaria on the Limits of Natural Wastage, Marriage and Lack of Commodity-Material Values in the their Storage and transportation. (2007). Sofia, Bulgaria (Bg) Available at: https://lex.bg/bg/laws/ldoc/-560170495. Last accessed: 15.07.2022

Patel, S. K. & Varshney, B. P. (2014). Modeling of wheat crop harvesting losses. *CIGR Journal, 16*(2), 97-102.

Rod, N. M., Asoodar, M. A. & Rahnema, M. (2013). Effect of combine working speed and seed moisture content on berseem clover losses in khouzestan. *International Journal of Agriculture and Crop Sciences*, *5*(4), 349-354.

Schulten, G. (1982). Post-harvest losses in tropical Africa and their prevention. *Food Nutr. Bull.*, *4*, 2–9.

Seth, M. K, Chandrakar, M. & Gauraha, A. K. (2018). Post harvest losses, marketing pattern and constraints of chick pea in northern hills of Chhattisgarh. *Economic Affairs*, *63*(2), 311-316.

Srivastava, A. K., Goering, C. E. & Rohrbach, V. (1993). Engineering principles of agricultural machines. *ASAE*, Textbook number 6.

Received: **October, 09, 2023**; *Approved*: **January, 12, 2024;** *Published:* **October, 2024**