EFFECT OF GRADED DIETARY INCLUSION LEVELS OF HYBRID RYE GRAIN ON PRODUCTIVE PERFORMANCE, THE COST-EFFECTIVENESS OF NUTRITION AND EGG QUALITY IN LAYING HENS

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Abstract

The study was designed to investigate productivity parameters, egg quality and the cost effectiveness of feeding laying hens with diets where ground wheat was replaced with varying levels of whole hybrid rye grain cv. Brasetto. A total of 396 Hy-Line Brown hens at 34 weeks of age were allocated to three treatment groups with 66 replicates (cages) of two hens each, and were fed isocaloric and isonitrogenous pelleted diets for 12 weeks. The diet for control group hens (R0) did not contain rye grain. In diets for hens from groups R100 and R200, ground wheat grain was partially replaced with whole rye grain at 100 g/kg and 200 g/kg, respectively. Whole intact rye grains were included in the diets. The cost of diets containing 10% and 20% of whole rye grain was by approximately 1.0% and 1.9% lower, respectively, compared with the control diet that contained no rye grain. During the entire 12-week feeding period, dietary treatments had no effect on laying rate (95.64% to 97.07%), egg weight (62.51 g to 62.74 g) or egg mass output (5.04 kg to 5.12 kg per hen). The inclusion of whole rye grain in layer diets caused a linear increase in feed intake ($P < 0.047$) and tended to linearly increase the feed conversion ratio (FCR, $P = 0.078$). Both groups of hens fed diets containing whole rye grain were characterized by a linear decrease in the dry matter (DM) content of excreta ($P = 0.001$). Increased excreta moisture was accompanied by a tendency towards a higher incidence of dirty eggshells in R200 hens ($P = 0.068$). The inclusion of 100 g/kg of whole rye grain in layer diets decreased the cost of feed per kg of eggs by 1.9%. Dietary treatments had no significant effect on eggshell thickness (0.330 mm–0.345 mm), albumen quality (Haugh units, 83.46–85.84) or yolk color (3.8–4.0). The results of this experiment indicate that pre-pellet inclusion of whole rye (at up to 200 g/kg) in diets with supplemental NSP-degrading enzymes and phytase can be an effective and economically viable alternative to ground wheat in pelleted layer diets.

Key words: whole hybrid rye, laying hens, productivity and profitability, egg quality

Poland is one of the largest European and global rye producers, with an annual production of 2.41 million tons (FAO, Faostat). The use of rye grain as a feed ingredient in intensive poultry farming is limited due to the presence of antinutritional factors, mostly the water-soluble fraction of non-starch polysaccharides (NSPs) amounting to around 150 g per kg of dry matter (DM), as well as alkylresorcinols and ergot (Annison and Choct, 1991; Jürgens et al., 2012). The digestive enzymes produced by birds are not capable of degrading NSPs, especially arabinoxylans (Choct et al., 1996). The high concentration of soluble NSPs in rye grain increases digesta viscosity, thus disrupting the movement of particles and solutes across the intestinal lumen and impeding the diffusion of digestive enzymes, which reduces the digestion and absorption of nutrients including essential minerals (Fengler and Marquardt, 1988; Smits and Annison, 1996; Tellez et al., 2014). Impaired gut function in young broilers and adult laying hens fed rye-containing diets negatively affects their performance by depressing the growth rate and feed conversion. Wet and viscous excreta, noted in birds fed such diets, is the primary cause of increased litter moisture leading to footpad dermatitis (FPD) (El-Wahab et al., 2013; Chuppava et al., 2018).

Breeding efforts and genetic progress have resulted in the development of new, improved rye varieties with a higher yield potential, and higher resistance to disease and adverse environmental conditions (Bujak and Dopierała, 2007; Skarżyńska and Pietrych, 2018). Rye plays an important role in sustainable agriculture because it is easy to grow and inexpensive, which contributes to the efficient utilization of rye grain as an ingredient of poultry diets.

Attempts have been made to include ground or whole rye gain, at various rates, in diets offered in mash form. One of earlier experiments investigating the nutritional value of ground rye as a feed ingredient for laying hens demonstrated that an increase in the rye content of diets (from 5% to 25%) led to a linear decrease in egg production and feed efficiency (Proudfoot and Hulan, 1986). Research shows that the addition of exogenous glycanases capable of degrading NSPs can alleviate the adverse effects of soluble arabinoxylans, improve the growth rate of birds and feed conversion, and reduce the incidence of dirty eggs in layers fed rye-containing diets (Smulikowska et al., 1997; He et al., 2003; Lázaro et al., 2003 a, b; Arczewska-Włosek et al., 2019; Bederska-Łojewska et al., 2019). However, several later studies revealed that

ground or whole rye included in mash layer diets at 30%–47% as a substitute for ground wheat or maize did not affect egg production or feed efficiency (Campbell and Campbell, 1989; Smulikowska et al., 1997; Pan et al., 1998; Lázaro et al., 2003 a, b).

Only a few studies have investigated the efficacy of new rye cultivars in poultry nutrition. Arczewska-Wlosek et al. (2019) reported that ground hybrid rye could be incorporated into broiler chicken diets at up to 20% after 22 days of age, whereas in starter diets, even 5% of ground rye grain negatively affected the growth rate of birds. El-Wahab et al. (2020 b) found that squashed rye added to supplementary pelleted feed at levels that were increased weekly (5%, 10%, 20%, 30%) had no negative effect on body weight gain or feed conversion in broilers. Bederska-Łojewska et al. (2019) demonstrated that in layer diets, the inclusion of 10% of ground hybrid rye instead of ground corn and wheat considerably decreased laying rates.

A review of the literature indicates that the results of previous studies investigating the efficacy of rye grain in laying hen nutrition are inconclusive. Therefore, the following hypothesis was verified in the present study: partial replacement of ground wheat grain with whole hybrid rye grain (at up to 20%) in layer diets, which were supplemented with exogenous enzymes (xylanase and phytase) and then pelleted, does not compromise laying hen productivity or egg quality. The aim of this experiment was to determine the effect of whole hybrid rye grain (cv. KWS Brasetto) at two dietary inclusion levels (100 g/kg and 200 g/kg) on productivity parameters, including laying intensity, egg weight and feed conversion ratio (FCR), and the quality traits of eggs in hens aged 34 to 46 weeks. The unit cost of whole rye-based diets and the cost-effectiveness of nutrition were also analyzed. The study was also designed to investigate the effect of whole rye on excreta moisture in hens in view of potential welfare/environmental issues.

Material and methods

Birds and housing

A total of 396 Hy-Line Brown hens at 34 weeks of age were placed in double-sided, three-tier battery cages on a wire mesh floor, in a building with a controlled environment. The hens were allocated to three dietary treatment groups, based on their body weight. The treatment groups were evenly distributed between the upper, middle and lower tiers to minimize the cage-level effect. Each group consisted of 66 replicates (cages), with two hens per cage (132 birds per group). Each cage (30 × 63 cm, with a floor slope of 12°) was equipped with individual nipple drinker. A metal feed trough and a wire egg collector were installed in the front of each cage. The hens were housed in a windowless room, with room temperature of 20 – 22°C and the light cycle of 16 h of continuous light (incandescent lighting, 10 lx) and 8 h of

dark. The trial lasted for 12 weeks, from 34 to 46 weeks of age. The routine animal care and experimental procedures used in this study conformed to the provisions of the Polish Law on Animal Protection (Act of 21 August 1997) and Resolution no. 13/2016 of the National Ethics Committee for Animal Experiments of 17 June 2016.

Table 1. Nutrient content of hybrid rye grain and wheat grain (g/kg, as-fed basis)

Item	Rye	Wheat
Analyzed content		
dry matter	877.3	880.0
crude protein	114.0	115.0
crude fat	19.9	17.0
starch	576.4	602.0
sugars	7.85	27.0
Calculated content ¹		
apparent metabolizable energy (MJ/kg)	12.86	12.52
non-starch polysaccharides	129.36	99.44
arginine	5.10	5.30
lysine	3.80	3.20
methionine	1.60	1.80
methionine + cysteine	3.90	4.40
threonine	3.30	3.30
tryptophan	1.20	1.30
calcium	0.80	0.70
total phosphorus	3.00	3.70
available phosphorus	1.20	1.30

¹Calculated from the Polish Feedstuff Analysis Tables (Smulikowska and Rutkowski, 2018). Apparent metabolizable energy was estimated using the equation of Fisher and McNab (1987): AME (MJ/kg) = ((0.155 × % crude protein) + (0.343 × % crude fat) + (0.167 × % starch) + (0.130 × % sugar)). NSP content was calculated according to Bach-Knudsen (1997).

Experimental design and diets

During the study period, the hens were fed three isonitrogenous and isocaloric wheat-SBM-based diets supplemented with 0 (control), 100 and 200 g/kg of whole rye grain as a substitute for ground wheat (groups R0, R100 and R200, respectively). A hybrid rye cv. KWS Brasetto, harvested in 2019, was obtained from the KWS – Lochow Polska Ltd., Kondratowice (Poland). The chemical composition of rye grain compared with wheat grain is given in Table 1. The diets were formulated to meet the nutrient requirements of laying hens of this age, i.e., to contain 2700 kcal of apparent metabolizable energy (AME)/kg and approximately 165 g of crude protein (CP)/kg (Smulikowska and Rutkowski, 2018). The composition and nutritional value of experimental diets are presented in Table 2. All diets contained the same amounts of corn (20%), rapeseed meal and sunflower meal (5% each) and alfalfa meal (3%). Whole intact rye grains were included in the diets. The remaining feed ingredient, before inclusion in the diets, were ground to pass through a 3-mm sieve in a hammer mill (Jesma Company, Sprout Mator, Denmark). The diets were also supplemented with

commercial enzyme preparations with xylanase activity of 1,000 FXU/g and phytase activity of 5,000 FYT/g. The lysine and methionine content of diets was balanced with the addition of pure amino acids, and the energy value of diets was balanced with soybean oil and a vegetable fatty acid concentrate. Complete diets were pelleted at 65°C using the pelletizer machine (Jesma Company, Esbjerg, Denmark). Throughout the experiment, the diets in pelleted form and water were available *ad libitum*.

Sampling collection and chemical analyses

Samples of wheat and rye were analyzed before formulating the diets (Association of Official Analytical Chemists, 2005) to determine their DM content by the oven drying method (934.01), CP content by the Kjeldahl method (954.01) and ether extract content by Soxhlet fat analysis (920.39). Reducing sugars were extracted from rye and wheat samples with 40% ethanol for 1 h, and their content was determined with the Luff-Schoorl method (PN-R-64784, 1994). The diets were also analyzed for their content of DM, CP and crude fat.

All birds were weighed individually at the beginning (34 weeks of age) and at the end of the trial (46 weeks of age) to determine average body weight gain. Hen mortality was recorded as it occurred. Eggs were collected every other day from each cage, and the average egg production rate was calculated and expressed on a hen-day basis (% hen/day). Egg damage rate was determined based on the number of eggs with dirty shells (stained with feces or blood) and damaged shells (broken eggs, cracked eggs and shell-less eggs). The weight of eggs was recorded every two weeks by weighing (AKA2200 scale, AXIS Ltd., Gdańsk, Poland, accuracy of 0.01 g) individually eggs laid over two days. Throughout the experiment, a total of over 1,200 eggs per group were used to calculate average egg weight. Egg mass output was calculated by multiplying egg weight by egg production. Feed intake was measured on a cage basis (leftovers were collected and weighed manually at 38, 42 and 46 weeks of age) and expressed as the average feed intake per hen. The FCR (kg of feed/kg of eggs) for each period was calculated on the basis of feed consumed as well as egg production and egg weight. The cost of experimental diets was calculated based on the net prices of feed ingredients (June 2020), and it was used to calculate feed cost per kg of eggs.

Excreta samples

After 4, 8 and 12 weeks of feeding experimental diets, 10 randomly selected cages from each group were equipped with excreta collection trays. Each time during one-day collection periods, fresh excreta were collected from the same 10 cages in each group four times daily (at 6-h intervals), and were stored in plastic bags at a temperature of 4°C. All excreta collected per cage were thoroughly mixed by hand into uniform mass, and samples (approx. 80 g) were taken to determine DM content (934.01 method; AOAC International, 2005).

Table 2. Ingredient composition, nutrient content (g/kg, as-fed basis) and cost of experimental diets

Item	Treatment		
	R0	R100	R200
Ingredient			
wheat	431.5	316.4	201.1
hybrid rye	–	100.0	200.0
maize	200.0	200.0	200.0
soybean meal	88.7	101.5	114.2
rapeseed meal	50.0	50.0	50.0
sunflower meal	50.0	50.0	50.0
alfalfa meal	30.0	30.0	30.0
soybean oil	11.0	11.8	12.7
vegetable fatty acid concentrate	21.9	23.6	25.4
NaCl	3.6	3.6	3.6
limestone	94.3	94.2	94.1
monocalcium phosphate	13.1	13.2	13.3
ronozyme WX ¹	0.2	0.2	0.2
ronozyme P ¹	0.1	0.1	0.1
choline chloride	0.7	0.7	0.7
L-Lysine 99 HCl	1.0	0.8	0.6
DL-Methionine 99	1.4	1.4	1.5
vitamin-mineral premix ²	2.5	2.5	2.5
Analyzed nutrient content			
dry matter	908.9	909.9	910.2
crude protein	161.3	166.0	168.2
crude fat	52.8	55.7	55.9
Calculated nutrient content³			
apparent metabolizable energy (MJ/kg)	11.30	11.30	11.30
non-starch polysaccharides (NSPs)	107.2	111.1	114.9
lysine	7.90	7.90	7.90
methionine + cysteine	7.20	7.20	7.20
threonine	6.00	6.00	6.00
calcium	39.00	39.00	39.00
available phosphorus	4.00	4.00	4.00
sodium	1.60	1.60	1.60
Cost of experimental diets (€/ton) ⁴	217.42	215.21	213.41

Rye (R) was applied at the following dietary levels: 0, 100, and 200 g/kg (R0, R100, R200, respectively), as a partial substitute for wheat.

¹Ronozyme WX (CT) with minimum xylanase activity of 1,000 FXU/g and Ronozyme P (CT) with phytase activity of 5,000 FYT/g; DSM Nutritional Products Ltd., Mszczonów, Poland).

²Supplied the following per kilogram of diet: 8 000 IU vitamin A, 2 500 IU vitamin D₃, 20 mg vitamin E, 1.0 mg vitamin K₃, 1.5 mg vitamin B₁, 4 mg vitamin B₂, 1.0 mg vitamin B₆, 0.02 mg vitamin B₁₂, 0.1 mg biotin, 25 mg nicotinic acid, 6.0 mg pantothenic acid, 65 mg Mn, 50 mg zinc, 45 mg I, 0.15 mg Se, 6 mg Cu.

³Calculated based on the chemical composition of rye and wheat grain (Table 1) and according to the Polish Feedstuff Analysis Tables (Smulikowska and Rutkowski, 2018). NSP content was calculated based on the values of the individual components according to Bach-Knudsen (1997).

⁴Calculated based on the prices of feed ingredients, including wheat – EUR 175.32 and rye – EUR 123.62 per ton (25 June 2020). Average exchange rate (National Bank of Poland): EUR 1 = 4.449 PLN, as of 25 June 2020.

Egg quality

In the last week of the experiment, egg and eggshell quality examinations were performed (shell weight, eggshell thickness, yolk weight, yolk color, albumen height and weight, and Haugh unit score). Eggs laid during one day, picked from 10 randomly selected cages in each group (20 eggs per group), were analyzed. Eggshell thickness was determined as the mean value of measurements performed at three different locations (middle, broad and narrow ends) with the use of a digital micrometer gauge (± 0.001 mm; Mitutoyo QuantuMike, Poland Ltd., Wrocław, Poland). Albumen quality (Haugh unit) and yolk color were evaluated using a digital Egg Analyzer[®] (Orka Food Technology Ltd., Ramat Hasharon, Israel). The Egg Analyzer is equipped with an electronic scale for measuring egg weight, and with a self-contained module for measuring the height of the dense albumen fraction and yolk color. The egg yolk with the albumen was placed on a tray, which was enclosed in a completely dark module of the egg quality measuring equipment. The Haugh unit (HU) was calculated automatically based on egg weight and albumen height, and yolk color intensity was measured on a scale of 1–16 according to the DSM Yolk Color Fan within only 4 seconds. Egg quality analyses were completed within 24 h of egg collection.

Statistical analysis

The results were processed statistically by one-way analysis of variance (ANOVA), using STATISTICA ver. 13 software (StatSoft Inc., 2014). Linear and quadratic polynomial contrasts were used to evaluate the effect of rye inclusion levels in experimental diets. In the statistical analysis of performance, each replicate (cage; $n = 66$) was considered as an experimental unit. Due to the presence of some zero values, the coefficients of defective eggs were transformed to arcsine sqrt $[(x + 0.5)/100]$ before analysis. Pearson's chi-square statistic in the analysis of contingency tables was used for mortality assessment. In the statistical analysis of egg quality pa-

rameters, each egg ($n = 20$) was considered as an experimental unit. The yolk color scores were analyzed by the Kruskal–Wallis test (non-parametric ANOVA). All data were expressed as arithmetic means with standard deviations (σ) and pooled standard errors of the mean (SEM). The differences between means were considered statistically significant at $P < 0.05$, whereas $0.05 < P > 0.10$ was considered a tendency.

Results

As shown in Table 1, rye grain, compared with wheat grain, had a lower content of CP (114.0 vs. 115.0 g/kg) and starch (576.4 vs. 602.0 g/kg), a nearly 3.5-fold lower content of sugars (7.85 vs. 27.0 g/kg), and a relatively higher content of crude fat (19.9 vs. 17.0 g/kg) and NSPs (129.4 vs. 99.4 g/kg) as well as higher AME values (12.86 vs. 12.52 MJ/kg). Relatively high lysine concentration and low concentration of methionine + cysteine were determined in rye grain (3.80 and 3.90 g/100g, respectively), compared with 3.20 and 4.40 g/100 g in wheat grain.

The experimental diets were formulated to be iso-caloric and iso-nitrogenous, containing 165 g/kg crude protein and 2700 kcal AME/kg (Table 2). Dietary inclusion of whole rye at 100 and 200 g/kg decreased the wheat content of diets from 431 g/kg (Diet R0) to 316 and 201 g/kg, respectively. Fat components (soybean oil and a vegetable fatty acid concentrate) were added to diets to level out their energy densities, proportionally to the decreasing wheat content and increasing soybean meal content. Increasing dietary inclusion levels of whole rye grain, added at the expense of ground wheat, led to an increase in the concentration of NSPs from 107 g/kg to 111 and 115 g/kg, respectively, in experimental diets (Table 2). The results of a chemical analysis of diets, including the concentrations of CP and crude fat, confirmed that they were consistent with the values adopted in the feeding program for laying hens.

Table 3. Production parameters of hens between weeks 1 and 4 of the trial (34 to 38 weeks of age)

Item	Treatment			Pooled SEM	P-value		
	R0	R100	R200		groups	linear	quadratic
Initial body weight (kg)	2.04 $\pm$ 0.10	2.04 $\pm$ 0.10	2.03 $\pm$ 0.10	0.007	0.923	ND	ND
Initial egg weight (g)	61.84 $\pm$ 2.69	62.11 $\pm$ 3.17	61.53 $\pm$ 2.88	0.210	0.534	ND	ND
Number of eggs per hen	26.99 $\pm$ 1.79	27.37 $\pm$ 1.72	27.01 $\pm$ 2.10	0.135	0.443	0.956	0.203
Laying rate (%)	96.39 $\pm$ 6.41	97.74 $\pm$ 6.15	96.46 $\pm$ 7.51	0.483	0.443	0.956	0.203
Egg mass output (kg/hen)	1.69 $\pm$ 0.13	1.71 $\pm$ 0.14	1.69 $\pm$ 0.15	0.010	0.483	0.768	0.243
Egg weight (g)	62.66 $\pm$ 2.82	62.55 $\pm$ 2.84	62.32 $\pm$ 2.70	0.200	0.781	0.491	0.893
Average feed intake (kg/hen)	3.32 $\pm$ 0.22	3.30 $\pm$ 0.24	3.36 $\pm$ 0.30	0.019	0.424	0.349	0.362
Daily feed intake (g/hen)	118.5 $\pm$ 8.1	117.9 $\pm$ 8.8	120.0 $\pm$ 10.9	0.668	0.424	0.349	0.362
Feed conversion ratio (kg/kg eggs)	1.97 $\pm$ 0.17	1.94 $\pm$ 0.15	2.01 $\pm$ 0.21	0.013	0.076	0.237	0.053
Mortality (birds/%)	1/0.78	3/2.34	2/1.54	ND	0.600	ND	ND
Excreta dry matter (%)	23.77 $\pm$ 2.12	21.86 $\pm$ 2.09	21.35 $\pm$ 2.51	0.441	0.056	0.023	0.429

Rye (R) was applied at the following dietary levels: 0, 100, and 200 g/kg (R0, R100, R200, respectively), as a partial substitute for wheat. ND = not determined.

Table 4. Production parameters of hens between weeks 5 and 8 of the trial (39 to 42 weeks of age)

Item	Treatment			Pooled SEM	P-value		
	R0	R100	R200		groups	linear	quadratic
Number of eggs per hen	26.92±1.89	27.12±1.40	26.93±1.95	0.127	0.763	0.977	0.463
Laying rate (%)	96.15±6.76	96.87±5.02	96.18±6.97	0.453	0.763	0.977	0.463
Egg mass output (kg/hen)	1.69±0.14	1.70±0.12	1.69±0.15	0.010	0.751	0.926	0.452
Egg weight (g)	62.73±3.02	62.85±2.86	62.77±2.92	0.210	0.972	0.938	0.822
Average feed intake (kg/hen)	3.15±0.18	3.17±0.20	3.19±0.26	0.016	0.603	0.316	0.978
Daily feed intake (g/hen)	112.4±6.6	113.1±7.0	113.8±9.4	1.163	0.603	0.316	0.978
Feed conversion ratio (kg/ kg eggs)	1.88±0.23	1.86±0.15	1.90±0.23	0.015	0.634	0.590	0.432
Mortality (birds/%)	0	1/0.78	0	ND	0.364	ND	ND
Excreta dry matter content (%)	23.77±2.24	22.85±1.35	22.54±2.08	0.353	0.346	0.165	0.686

Rye (R) was applied at the following dietary levels: 0, 100, and 200 g/kg (R0, R100, R200, respectively), as a partial substitute for wheat.

ND = not determined.

Table 5. Production parameters of hens between weeks 9 and 12 week of the trial (43 to 46 weeks of age)

Item	Treatment			Pooled SEM	P-value		
	R0	R100	R200		groups	linear	quadratic
Final body weight (kg)	2.12±0.14	2.13±0.13	2.10±0.15	0.010	0.391	0.267	0.424
Number of eggs per hen	26.44±1.58	27.13±0.98	26.50±2.57	0.133	0.065	0.866	0.020
Laying rate (%)	94.45±5.66	96.90±3.49	94.64±9.18	0.476	0.064	0.866	0.020
Egg mass output (kg/hen)	1.66±0.11	1.71±0.10	1.67±0.18	0.010	0.062	0.887	0.019
Egg weight (g)	62.86±2.96	63.10±2.78	62.82±3.15	0.213	0.853	0.945	0.576
Average feed intake (kg/hen)	3.19 b±0.24	3.27 ab±0.22	3.32 a±0.21	0.017	0.004	0.001	0.674
Daily feed intake (g/hen)	113.7 b±8.6	116.6 ab±7.8	118.5 a±7.6	0.591	0.004	0.001	0.674
Feed conversion ratio (kg/ kg eggs)	1.92 b±0.23	1.91 b±0.14	2.02 a±0.31	0.016	0.007	0.010	0.069
Mortality (birds/%)	0	0	0	ND	ND	ND	ND
Excreta dry matter content (%)	22.92±2.56	21.69±1.87	21.09±1.95	0.404	0.170	0.067	0.709

Rye (R) was applied at the following dietary levels: 0, 100, and 200 g/kg (R0, R100, R200, respectively), as a partial substitute for wheat.

ND = not determined.

a-b – means within the same line with no common letters differ significantly ($P < 0.05$) based on Tukey's comparison of means.

Table 6. The cumulative effect of whole rye grain on laying performance, feed cost per kg of eggs and excreta DM content between weeks 1 and 12 of the trial (34 to 46 weeks of age)

Item	Treatment			Pooled SEM	P-value		
	R0	R100	R200		groups	linear	quadratic
Number of eggs per hen	80.34±4.46	81.54±3.50	80.45±6.04	0.345	0.294	0.893	0.119
Laying rate (%)	95.64±5.31	97.07±4.17	95.78±7.19	0.411	0.294	0.893	0.119
Egg damage rate (%)	1.85±3.05	1.59±2.63	1.38±1.31	0.175	0.673	ND	ND
including:							
dirty eggshells	0.87±1.56	0.85±1.62	1.04±1.04	0.102	0.068	ND	ND
damaged eggshells	0.98±2.74	0.74±1.59	0.33±0.64	0.135	0.130	ND	ND
Egg weight (g)	62.64±2.78	62.74±2.71	62.51±2.82	0.199	0.895	0.790	0.699
Egg mass output (kg/hen)	5.04±0.32	5.12±0.326	5.04±0.44	0.026	0.316	0.999	0.129
Average feed intake (kg/hen)	9.65±0.56	9.73±0.65	9.86±0.67	0.044	0.130	0.047	0.754
Daily feed intake (g/hen)	114.9±6.7	115.8±6.7	117.4±8.0	0.519	0.130	0.047	0.754
Feed conversion ratio (kg/ kg eggs)	1.92 ab ±0.13	1.90 b±0.12	1.97 a±0.22	0.012	0.049	0.078	0.087
Feed cost (€/kg eggs) ¹	0.417±0.03	0.409±0.03	0.420±0.05	0.003	0.186	0.603	0.079
	100%	98.1%	100.7%				
Mortality (birds/%)	1/0.78%	4/3.12%	2/1.54%	ND	0.357	ND	ND
Excreta DM content (%)	23.49 a±2.27	22.13 b±1.81	21.66 b±2.21	0.234	0.003	0.001	0.357
Body weight gain (kg)	0.09±0.08	0.09±0.09	0.07±0.10	0.007	0.243	0.153	0.379

Rye (R) was applied at the following dietary levels: 0, 100, and 200 g/kg (R0, R100, R200, respectively), as a partial substitute for wheat.

ND = not determined.

a-b – means within the same line with no common letters differ significantly ($P < 0.05$) based on Tukey's comparison of means.

¹Average exchange rate (National Bank of Poland): EUR 1 = 4.4495 PLN, as of 25 June 2020.

Table 7. Egg quality characteristics in laying hens fed diets with different dietary inclusion levels of hybrid rye grain

Item	Treatment			Pooled SEM	P-value		
	R0	R100	R200		groups	linear	quadratic
Eggshell weight (g)	6.42±0.38	6.69±0.60	6.59±0.46	0.064	0.219	0.289	0.165
Eggshell proportion (%)	10.33±0.62	10.72±0.94	10.55±0.71	0.100	0.281	0.372	0.187
Eggshell thickness (mm)	0.330±0.02	0.341±0.03	0.345±0.02	0.003	0.184	0.077	0.628
Albumen weight (g)	39.15±0.94	39.45±0.85	39.53±1.62	0.152	0.562	0.309	0.742
Albumen proportion (%)	63.01±1.48	63.24±1.07	63.36±2.60	0.234	0.823	0.541	0.911
Albumen height (mm)	7.33±1.13	7.52±0.77	7.14±0.92	0.123	0.467	0.531	0.289
Albumen Haugh unit	84.49±7.17	85.84±4.68	83.46±5.99	0.776	0.461	0.590	0.263
Yolk weight (g)	16.57±0.86	16.24±0.75	16.28±1.52	0.141	0.586	0.407	0.541
Yolk proportion (%)	26.66±1.34	26.04±1.27	26.09±2.41	0.225	0.458	0.302	0.483
Yolk color score	4.00±0.46	3.85±0.49	3.80±0.52	0.063	0.412	ND	ND

Rye (R) was applied at the following dietary levels: 0, 100, and 200 g/kg (R0, R100, R200, respectively), as a partial substitute for wheat.

Data are means of randomly sampled 20 eggs per treatment.

ND = not determined.

During this study, the average price of rye grain in Poland (EUR 123.62 per ton) was lower than the average price of wheat grain (EUR 175.32) by around 30% (Table 1). As a result, the average cost of feed ingredients in diets R100 (EUR 215.21) and R200 (EUR 213.41) was lower by approximately 1.0% and 1.9%, respectively, compared with the control diet R0 (EUR 217.42 per ton) that contained no rye grain (Table 2).

At the beginning of the experiment, the body weights of 34-week-old hens and the average egg weight were similar in all groups ($P = 0.923$ and $P = 0.534$, respectively, Table 3). In weeks 1–4 and 5–8 of the trial, whole rye grain had no effect on the productivity of laying hens, including laying rate and egg weight as well as feed intake and FCR (Tables 3 and 4). In weeks 4 and 12, a linear decrease in the DM content of excreta was noted in hens fed whole rye-based diets ($P = 0.023$ and $P = 0.067$). In weeks 9–12 of the trial, bird deaths were not recorded, and laying rate, egg weight and egg mass output were comparable in all groups (Table 5). An increase in laying rate and egg mass output was noted in group R100 ($P = 0.065$). During this period, increasing dietary inclusion levels of whole rye grain up to 200 g/kg linearly increased feed intake ($P = 0.001$) and FCR ($P = 0.010$). In comparison with the control group, hens fed diet R200 were characterized by significantly higher daily feed intake (118.5 vs. 113.7 g) and feed consumption per kg of eggs (2.02 vs. 1.92 kg).

The cumulative effect of whole rye grain on laying performance, feed cost per kg of eggs and excreta DM content between 34 to 46 weeks of age is presented in Table 6. The productivity parameters such as laying rate (95.64–97.07%) and average egg weight (62.51–62.74 g) were similar in all treatments ($P = 0.294$ and $P = 0.895$, respectively). Diets containing rye grain had no influence on the incidence of egg defects (1.38–1.85%), but the percentage of eggs with dirty shells (stained with feces) tended to be higher in group R200 ($P = 0.068$). In-

creasing dietary inclusion levels of whole rye grain up to 200 g/kg linearly increased feed intake ($P = 0.047$) and tended to linearly increase the FCR ($P = 0.078$). The cost of feed per kg of eggs was comparable in groups R0 and R200, whereas the inclusion of 10% of rye grain in diets (group R100) decreased the cost of consumed feed by 2.2%. Mortality was low throughout the trial (1 to 4 birds per group in total) and it was not related to the dietary treatments ($P = 0.357$). The body weight gain was similar in all groups (66 g–91 g; $P = 0.243$). Whole rye-based diets linearly increased excreta moisture ($P = 0.001$) because the DM content of excreta in laying hens fed diets R100 and R200 (22.13% and 21.66%) was significantly lower than in control birds fed diet R0 (23.49%, $P = 0.003$). Although this study did not aim to evaluate the severity of footpad dermatitis, the foot pads of hens were inspected visually during final weighing. The evaluation revealed that the condition of foot pads was excellent, and no symptoms of footpad dermatitis were observed (data not shown).

The incorporation of rye grain into layer diets had no effect on eggshell or interior egg quality parameters (Table 7). Eggshell thickness (0.330–0.345 mm), the proportions of egg morphological components (albumen, yolk, eggshell) and yolk color score (3.8–4.0) were similar in all groups. Egg albumen quality was good since the Haugh unit values were relatively high (83.46–85.84) and did not differ among groups.

Discussion

In the present experiment, ground wheat was partially replaced with 100 g/kg and 200 g/kg of whole intact rye grain in diets for laying hens aged 34 to 46 weeks. It is well known that the poorly digested, viscous pentosan in the endosperm cell wall is the major causative factor for the low nutritional value of rye (Fengler and Marquardt,

1988). The authors intended to determine the effect of the pre-pellet inclusion of whole intact rye grain in diets supplemented with NSP-degrading enzyme (xylanase) and phytase on egg production and quality. All complete diets were then pelleted and offered to birds. Phytase is known to increase the availability of many nutrients apart from P, such as Ca, Mg, Fe, Cu and Mn, as well as protein and energy (Silversides et al., 2006). Structural components such as coarse particles and whole grains have been widely used in poultry diets. It has been suggested that the pre-pellet inclusion of whole grain and its coarse particles in poultry diets contribute to increasing gizzard size, and stimulate gut motility and pancreatic secretion (Truong et al., 2017; Ege et al., 2019; El-Wahab et al., 2020 a). Pretreatment of rye by pelleting prior to enzyme supplementation has also been shown to enhance the susceptibility of the viscous-causing carbohydrates to enzymatic degradation and the subsequent response of birds fed such diets (Bedford et al., 1991; Teitge et al., 1991).

The results of this study indicate that the supplementation of whole rye-based diets with NSP-degrading enzymes and phytase can be a good practice in layer nutrition. It was found that the dietary whole rye content of up to 200 g/kg was not a limiting factor for egg production efficiency since the dietary treatments had no adverse effect on laying rate (95.64–97.07%). Moreover, other key productivity parameters such as egg weight (62.51–62.74g) and egg mass output (5.04–5.12 kg) in hens fed rye-based diets were comparable with those determined in the control group. The values of feed consumption and FCR can be considered satisfactory; despite a minor increase in daily feed intake (by 2.0%) and FCR (by 2.6%) in hens fed 200 g/kg of rye, the cost of feed per kg of eggs was similar to that in the control group. Due to its low price, rye grain is an attractive feed ingredient for formulating layer diets, which was confirmed in this study; the inclusion of 100 g/kg of whole rye grain in layer diets decreased the cost of feed per kg of eggs by 1.9%.

The results of previous experiments (Campbell and Campbell, 1989; Smulikowska et al., 1997) showed that 30%–47% inclusion level of rye grain supported comparable egg production to wheat-based or maize-based control diets. Such an inclusion rate of rye grain had no effect on hen-day egg production, feed efficiency per dozen eggs or egg quality. Lázaro et al. (2003 a) also demonstrated that diets containing 35% of ground rye as a substitute for ground maize did not affect laying rate or feed efficiency, but hens fed rye-based diets exhibited a higher incidence of dirty eggs. In a recent study, Bederska-Łojewska et al. (2019) found that ground rye incorporated into layers diets at 100–200 g/kg (i.e. the amount identical to that in the present study) significantly decreased laying rate, but it had no negative influence on feed intake or feed conversion ratio. According to the cited authors, the lower laying rates resulted from poorer digestion of rye-derived nutrients due to the high content of soluble NSPs.

The differences between the above findings may be due to the nature of the rye samples used or different rye AME values adopted for the formulation of diets. The AME of rye grain used in this experiment was estimated at 12.86 MJ/kg, and a similar value was reported for squashed rye by Abd El-Wahab et al. (2020 b), whereas lower values (10.3–12.00 MJ/kg) are given in the Feedstuff Analysis Tables for Poultry (Janssen, 1989; NRC, 1994; Smulikowska and Rutkowski, 2018).

In the present study, increased excreta moisture and the related, potential intestinal disorders were the main manifestation of the dietary inclusion of whole rye grain. Increased excreta moisture was accompanied by a somewhat higher incidence of dirty eggs. It is believed that NSPs can influence the level of moisture due to their water-holding capacity because 1 g of NSPs can hold up to 10 g of water, and fully cross-linked arabinoxylans hold up to 100 g of water per g of the polymer (Izydorczyk and Biliaderis, 1995). The control of excreta/litter moisture and quality is a priority in the modern poultry industry, to avoid environmental and animal welfare problems and to reduce productivity losses. It is well known that high concentrations of hardly digestible soluble NSPs in poultry diets enhance digesta moisture, impair nutrient absorption and may compromise the growth and performance of birds (Bedford and Classen, 1992; Smits and Annison, 1996; Iji, 1999). Increased digesta viscosity is usually accompanied by increased excreta moisture, which may increase the incidence of pasty vents in broiler chickens and the percentage of dirty eggshells in laying hens fed rye-based diets (Pan et al., 1998; Silva and Smithard, 2002; Lázaro et al., 2003 a, b). In floor housing systems, increased litter moisture and constant contact of foot pads with wet litter are the main predisposing factors for FPD lesions (El-Wahab et al., 2013; Chuppava et al., 2018). In the current experiment, hens were kept in cages, therefore the only consequence of increased excreta moisture content was a minor increase in the percentage of dirty eggshells in hens fed rye-based diets. According to estimates of the egg processing industry, dirty eggs represent approximately 4% of the total egg production (Choct et al., 1999).

In the present study, whole rye grain had no effect on the analyzed egg quality parameters, which corroborates the findings of other authors (Campbell and Campbell, 1989; Smulikowska et al., 1997; Pan et al., 1998; Lázaro et al., 2003 a; Bederska-Łojewska et al., 2019). Significantly decreased intensity of yolk color in hens fed rye-based diets, reported by Bederska-Łojewska et al. (2019), was most likely caused by a low content of carotenoid-rich maize in the analyzed diets.

The results of this experiment indicate that whole rye grain can be an alternative to ground wheat as an energy source in layer diets. It can be added at up to 20% without compromising hen productivity or egg quality. Whole rye grain can also be an effective and economically viable substitute for ground wheat in complete layer diets. The inclusion of 10% of whole rye grain in layer diets de-

creased the cost of feed per kg of eggs by 2.2%, based on the market prices of rye and wheat. However, the diets containing 10% and 20% of rye grain significantly increased excreta moisture. Wet droppings can be problematic especially in tiered cage systems.

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