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The productivity, quality and bread-making properties of organically and conventionally grown winter rye

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Abstract

Rye in combination with wheat is the major bread grain in northern Europe. Consuming rye whole grain products provides a rich source of dietary fibre as well as several bioactive compounds with potentially positive health implications. Due to limited research data concerning rye growing under different cultivation systems, there is also a lack of information on the influence of these systems on the quality properties of rye breads. The goal of the research was to compare the responses of rye to the conditions of organic and conventional management. The analysed properties included grain yield and quality, followed by the quality properties of whole grain flour, and ending with those of the end-product. Baking tests were carried out by using sourdough fermentation, and the pasting behaviours of rye flours were assessed using the Brabender Viscograph. Rye was grown on a sandy loam *Albic Stagnic Luvisol* (*LVab-st*) in a five-year crop rotation. Red clover was ploughed into the soil as green manure before rye sowing. For the organic treatment, no agrichemicals were used. For the conventional treatment, mineral fertilizers ($N_{83}P_{30}K_{75}$ kg ha^{-1} in total) and herbicides were applied.

The results of this seven-year experiment showed that the grain yield by the organic treatment was 64% of that obtained by the conventional treatment. For the conventional treatment, the protein content was significantly ($P < 0.05$) higher than for the organic treatment. An inverse correlation ($r = -0.596$) was determined between protein and starch contents of rye whole grain flour. Although several differences occurred in the flour properties and fluctuations in the viscograms for the organic and conventional treatments, no significant differences in the properties of breads were established between the treatments. Consequently, the breads baked by using whole grain flour derived from organically and conventionally cultivated rye were practically of the same quality.

Keywords: falling number, grain yield, loaf volume, protein, sourdough, starch.

Introduction

The interest in healthy food is increasing worldwide, bringing about also a growth in consumer demand for fibre-rich products. Products containing rye are the best representatives of this food group. As rye is mainly used in the form of whole grain products, it serves as a rich source of dietary fibre as well as of several classes of phytochemicals, bioactive compounds with potentially positive health implications (Poutanen et al., 2009; Åman et al., 2010; Bach Knudsen et al., 2017; Koistinen, Hanhineva, 2017). Nutritionists worldwide recommend consumption of cereal whole grain based products for the reason of their health benefits related to the regulation of blood glucose levels and the reduction of the risk of cardiovascular diseases and certain types of cancer (Rye and health, 2002, http://rye.vtt.fi/rye&health.pdf; Poutanen et al., 2009; Fardet, 2010; Åman et al., 2010; Dvořákova et al., 2012). The chemical composition of rye grain differs from that of wheat: rye contains less starch and protein but more free sugars and dietary fibre than wheat (Rye and health, 2002; Ауэрман, 2003). Starch characteristics, α-amylase activity, concentration of arabinoxylans and the presence of the enzymes used for their hydrolysis are the main quality factors influencing rheological properties of the rye dough (Banu et al., 2011). Polysaccharides that are the constituents of cell walls in rye endosperm are very important for rheological and baking properties of rye bread (Åman al., 2010). Water-extractable arabinoxylans have beneficial effects on the processability of the rye dough and the resulting bread as they increase the viscosity of the dough, improve bread crumb and volume, and delay starch retrogradation (Nowotna et al., 2006; Banu et al., 2011).

Wholemeal rye bread cannot be produced without a fermentation process. Sourdough, being a key element in traditional rye bread baking, is a mixture of flour and water with lactic acid bacteria and yeasts (Poutanen et al., 2009; Viiard et al., 2016). Sourdough contributes significantly to the dough processability, and to the flavour and texture of the bread. Also, it has been shown effective for the solution of minerals contained in bread cereals (Poutanen et al., 2009). The prolonged sourdough fermentation has been demonstrated to maintain the content of thiamine (B_1) and nicotinamide (B_3) during the rye bread baking (Martinez-Villaluenga et al., 2009; Poutanen et al., 2009; Mihhalevski et al.,

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2013). In addition, the ratio of soluble to insoluble dietary fibre increased during rye sourdough processing. The antioxidant capacity of traditional rye breads baked with sourdough has been shown to be clearly higher than of common white bread (Michalska et al., 2007; Martinez-Villaluenga et al., 2009).

According to the results of numerous investigations, the productivity of organically cultivated crops is reduced (by 21% in cereals) compared to conventionally cultivated crops (De Ponti et al., 2012). On the other hand, organically produced plant foods are generally considered preferable for their health impacts (Lundegårdh, Mårtensson, 2003). No information is available on the relationship between the growing methods and the quality properties of rye. However, Basinskiene et al. (2011), investigating the activity of several enzymes in organically and conventionally grown cereals (rye among them), concluded that organic farming system could produce cereals similar in quality to the conventional one. While research by Punia and Kheterpaul (2008), demonstrated no difference in the baking quality properties of wheat in relation to the farming system, some researchers (Annett et al., 2007), on the contrary, have found certain differences in rheological and baking properties of wheat depending on the growing methods.

Due to the very limited information concerning winter rye cultivation in differently managed crop rotations, in the present work we set the following objectives: to compare the responses of rye in the conditions of organic and conventional managements – beginning with the influence of the management system on the grain yield and quality properties, followed by the comparison of the rye flour properties, and ending with the comparison of the quality indices of baked breads. Our study hypothesizes that the breads baked with the help of sourdough fermentation by using whole grain flours of rye derived from organically and conventionally managed crop rotations are practically of the same quality.

Materials and methods

Field experiments. Site and soil description. The field experiment was performed in Central Estonia at Olustvere (58°33′ N, 25°34′ E) in 2008–2014. The soil type was sandy loam *Albic Stagnic Luvisol* (*LVab-st*) according to the WRB (2014) classification. Before the research period, the 6-hectare-area covering five crop rotation fields had been cultivated according to the principles of organic farming, with no fertilizer and pesticide use in 2002–2007. Before the experiment, the average agrochemical parameters of the soil were the following: pH_{KCl} – 6.0, organic matter content – 2.8%, P_{AL} – 96 (high level), K_{AL} – 108 (medium level), Ca_{NH4OAc} – 735 and Mg_{NH4OAc} – 64 mg kg^{-1}.

Experimental design. In 2007, the crop rotation was somewhat modified to the following chronological order: red clover (*Trifolium pratense* L.) → winter rye (*Secale cereale* L.) → potato (*Solanum tuberosum* L.) → oats (*Avena sativa* L.) → barley (*Hordeum vulgare* L.) with undersown clover. The size of each field was 1.2 ha, which was divided into three equal parts (0.4 ha) for separate cultivation methods. The following treatment methods were applied: organic without manure (ORG), organic with solid cattle farmyard manure (ORGFYM) and conventional (CONV) where solid cattle manure, mineral fertilizers and pesticides were used. For the purpose of the present work, we will compare only the organic and conventional treatments. We will not focus on the ORGFYM treatment because due to the crop rotation order, this treatment was only introduced in 2011.

For all the treatments, red clover was used as green manure – in the beginning of July, about two weeks after cutting the whole mass of clover, it was ploughed into the soil. Straw and crop residues were not removed from the field. In autumn, mouldboard ploughing at 20 cm depth was carried out in the fields. In the conventional treatment, straw-based cattle farmyard manure (FYM) was applied at a rate of 60 t ha^{-1} fresh weight (i.e. 8.3 t ha^{-1} of organic dry matter) prior to the rye stubble ploughing. According to the average data of manure analysed yearly, the following amounts of nutrients were applied with FYM: 286 kg ha^{-1} nitrogen (N), 61 kg ha^{-1} phosphorus (P), 166 kg ha^{-1} potassium (K), 130 kg ha^{-1} calcium (Ca) and 56 kg ha^{-1} magnesium (Mg); trace elements: 286 g ha^{-1} copper (Cu), 1224 g ha^{-1} manganese (Mn) and 201 g ha^{-1} boron (B). At this point, it is important to take into consideration that it is highly improbable that the residual impact of those nutrients could have been present for rye sown four years later. For the conventional treatment, in addition to the nutrients applied with FYM, the following amounts of nutrients were applied with mineral complex fertilizers during the five-year crop rotation: for potato – N 60 P 60 K 120 kg ha^{-1}, oats – N 72 P 18 K 36 kg ha^{-1}, barley with undersown clover – N 48 P 12 K 24 kg ha^{-1}. For the organic treatment, no fertilisers were used for any rotation crop.

Winter rye cultivar 'Elvi', seeding rate 450 seeds per 1 m^2, was sown during the period between 28 August (2013) and 13 September (2008). For the conventional treatment, mineral N 15 P 30 K 75 kg ha^{-1}, as complex fertilizer was applied during sowing. In April, after resumption of vegetation, rye was top-dressed with nitrogen (N 34 kg ha^{-1} as ammonium nitrate). After 3–4 weeks, the second dose of nitrogen (N 34 kg ha^{-1}) was applied.

For both organic and conventional treatments, weeds in the cereal fields were mechanically controlled by spring-time harrow. The area of the conventional treatment was also treated with several synthetic pesticides. For rye, the following herbicides were applied: in 2008–2011 – Secator (a.i. amidosulfuron 100 g l^{-1}, iodosulfuron-methyl-sodium 25 g l^{-1}, rate 150 ml ha^{-1}), 2012 – Mustang Forte (a.i. florasulam 5 g l^{-1}, aminopyralid 10 g l^{-1}, 2.4-D 180 g l^{-1}, 700 ml ha^{-1}), 2013 – Tomigan 180 EC (a.i. fluroxypyr 180 g l^{-1}, 500 ml ha^{-1}) + Trimmer 50SG (a.i. methyl-tribenuron 500 g kg^{-1}, 18 g ha^{-1}) and 2014 – Granstar Preemia 50SX (a.i. methyl-tribenuron 500 g kg^{-1}, 15 g ha^{-1}) + Primus XL (a.i. fluroxypyr 100 g l^{-1}, florasulam 5 g l^{-1}, 700 ml ha^{-1}).

At the maturity stage, before combine-harvesting of rye, four replications of sheaves from a 1 m^2 area were collected from the plots of both treatments. The ears were cut, and dried in laboratory conditions. The grains were threshed by hand and sorted through a 1.8 mm grain sieve (ISO 5223:1995 - Test sieves for cereals). The grain yield was quantified on 86% dry matter content. For both organic and conventional treatments, the grains of four replications were put together, and the composite grain samples for quality analyses were composed. For both treatments, matured rye on the 400 m^2 plots was harvested by a John Deere combine in the last few days of July or in the first week of August. The rye yield was dried and sorted in the experimental drier of the Olustvere training farm, Estonia. After that, by simple random sampling, the representative rye grain samples (each about 5 kg) were composed for the rheological analyses and baking tests.

Weather conditions. The detailed data from the nearest Meteorological Station at Viljandi (58°22′ N, 25°35′ E) on the monthly (January to December) precipitation and air temperatures during the experimental years (2008–2014) have been presented in Järvan et al. (2017). Success in winter rye production is highly dependent on the weather conditions, especially during the winter months. During the seven-year experimental period, the weather conditions were quite changeable. In the winters of 2010–2011 and 2012–2013, the extraordinary severe wintering conditions for rye plants prevailed and, because of this, a high number of plants perished through snow mould and/or other plant diseases.

In Estonia, the vegetation period for rye in the second year usually begins in the middle of April and the harvesting takes place at the end of July or in early August (Tupits, 2008). For this four-month period, the meteorological data (Table 1) indicate that the precipitation from the beginning of April to the end of July varied from 157 mm (2011) to 288 mm (2012). 2010 was a year characterized by below average (208 mm) and 2014 by above average (283 mm) rainfall during the main growth period. In 2008–2014, the average precipitation (April–July) reached 233 mm, and the average air temperature for this period was 13.0°C. Early springs of 2012 and 2013 were the coldest during the experimental years, which delayed the start of rye vegetation. The earliest spring during the experiment occurred in 2014, triggering rye growth already in March and allowing an earlier (4th April) application of the first dose of nitrogen. In July 2010, 2011 and 2014, extraordinarily high monthly average air temperatures (from 19.7°C to 22.4°C) prevailed. May and June of 2013 were unexpectedly warm, up to 3–4°C higher than the multi-annual average.

Table 1. Monthly total precipitation and average air temperatures from April to July, 2008–2014

Month	Year						
	2008	2009	2010	2011	2012	2013	2014
Precipitation mm							
April	52	17	35	11	53	44	15
May	22	17	53	58	62	75	88
June	119	91	77	22	81	21	108
July	48	136	43	66	92	51	72
Total	241	261	208	157	288	191	283
Temperature ºC							
April	7.2	6.0	6.0	6.7	4.9	3.6	6.7
May	10.8	11.6	12.3	11.3	11.8	14.5	11.8
June	14.6	13.9	14.7	17.8	13.7	18.0	13.7
July	16.5	17.2	22.4	20.4	18.2	17.8	19.7
Average	12.3	12.2	13.8	14.0	12.1	13.5	13.0

Analytical methods. The chemical analysis of rye grains was carried out at the Biochemistry Laboratory of the Estonian University of Life Sciences. The contents of phosphorus (P), calcium (Ca) and magnesium (Mg) were determined in Kjeldahl digestion by Fiastar 5000 (Foss, Denmark). Potassium (K) was determined by the flame photometric method, and nitrogen (N) by the copper catalyst Kjeldahl method (AOAC, 1990). The protein content in rye grains was determined according to ISO 20483:2013 (Determination of the nitrogen content and calculation of the crude protein content). The 1000 kernel weight was determined in four replications using the seed counter Numigral (ISO 520:2010 - Determination of the mass of 1000 grains). Rheological analyses and baking tests were performed in the Plant Production Laboratory of the Agricultural Research Centre at Saku, Estonia. The grain samples, after-matured for two months, were grinded by the QC 109 mill, using a coarse sieve (1.7 mm). Whole grain rye flours were left to mature for a month, then their quality parameters were determined: moisture – according to ICC 110/1:1976 (Determination of the moisture content of cereals and cereal products), crude protein – according to ISO 20483:2013 using Kjeltec-Auto 1030 Analyser and a digestion block, falling number according to ISO 3093:2010 (Determination of the falling number according to Hagberg-Perten) using FN1800, ash content – according to ICC 104/1:1990 (Determination of ash in cereals and cereal products), starch content – according to Commission Regulation (EC) No. 152/2009 III Annex L. Wheat flour for baking quality: origin Finland, protein 11.9%, falling number 320 sec, wet gluten 28.1%, gluten index 98%, ash content 0.54%, water absorption 57.1%, dough development time 2 min, stability 8 min.

Preparation of natural rye flour leaven (in 2008). First phase: 500 g whole grain rye flour + 400 ml water + 30 g pressed yeast, total weight 930 g, fermentation at temperature 26–28°C for 7–8 hours. Second phase: adding 500 g whole grain rye flour + 350 ml water to the leaven from the first phase, total weight 1780 g, fermentation at temperature 28°C for 7 hours. Third phase: 800 ml water and 700 g whole rye flour added to 600 g of the second phase leaven, mixture fermented for 4–4.5 hours until the final acidity of leaven is 12–13°, then stored in a freezer at −18°C.

Dough preparing and baking procedure. Natural rye flour leaven that had been stored in a freezer at −18°C was used for baking. Before use, the leaven was melted at room temperature and refreshed by adding rye flour and water. The recipe for the rye bread: rye leaven 525 g, testing whole rye flour 600 g, wheat flour 350 g, salt 28 g, sugar 60 g, pressed yeast 10.5 g. Amount of the water added was calculated as follows: [content of dry matter of added components × 100 / (100 – moisture content of dough)] – total weight of added components. Moisture content of leaven was ~50%. Using wheat flour was necessary for several reasons (element for yeast, increasing volume of bread baked from whole rye flour).

All compared bakings were done on the same day. The recipe was the same and the developed baking technology was followed exactly. The dough was mixed by hand in laboratory conditions. The quantity of leaven for the baking process was calculated so that 2/3 of leaven would be used for dough and 1/3 prepared as an ingredient for the next day's baking. The components of dough were mixed in a bowl for about 4–6 minutes. The temperature of the water added was calculated on the premises that the starting temperature of dough should be 27–28°C. The mixing bowl was covered with moist linen cloth and left in a thermostat at 28°C for about 2 hours (depending on the acidity of the dough). The fermented dough portions intended for comparison were divided into three equal parts each and weighed. Loaves were put into oiled baking bowls and left in a thermostat at 38°C, the rising time was approximately 60 minutes. The baking regime: 10 min at 260°C and 35 min at 210°C. After baking, the bread loaves were covered with a towel and left to cool. After a few hours, each loaf was put into a plastic bag. Next morning, each loaf was weighed. Loaf volume was measured using the rapeseed displacement method according to AACC method 10-05.01 (http://methods.aaccnet.org/summaries/10-05-01.aspx). The volume of bread is presented as an average of three loaves (Table 3). Specific volume was calculated as the ratio of bread loaf volume to loaf weight. Result was expressed in $cm^3 g^{-1}$. Bread crumb acidity was determined according to EVS 725:1996 (Determination of acidity).

The flour samples derived from the rye yields of 2012, 2013 and 2014 were investigated also in respect of their rheological properties. Their pasting behaviour was assessed using the Brabender Viscograph (Brabender oHG, Germany). The viscographic test (ICC standard No. 169 - Method for using the Brabender Viscograph) of flours involves a temperature program to demonstrate and characterise the behaviour of starch and the recording of the viscosity of the sample continuously (viscogram). The analysis starts with the decomposition and expansion of starch. The process begins at 50–60°C. As the water penetrates the starch granules, the volume of the granules increases up to 10 times, indicating the viscosity of the starch. The viscosity peaks at 80–90°C.

Statistical analysis. The annual results of the yield and quality parameters of rye grains were based on four replicates. The average data concerning the yield, quality parameters of grain, flour and breads during the experiment period (2008–2014) were based on seven replicates. The means for both organic and conventional treatments were compared using the least significant differences ($LSD_{0.05}$) ($P \leq 0.05$).

Results and discussion

Grain yield and quality. Winter rye, in general, is not demanding concerning soil fertility, which is why it is an appropriate crop for cultivation in organically managed crop rotations. In a wide range of soil types, rye can thrive with a good yielding capacity. In soils of high natural fertility, rye can produce grain yields of moderate size for prolonged periods even without nutrient input. The previously mentioned properties were proven also in our experiment: in the sandy loam soil where no fertilizers had been applied since 2002, the grain yields in the organic treatment group reached up to 3–4 t ha^{-1} even after a number of years (Table 2). Such a yield level for the organic treatment could be retained due to a number of factors: the high natural fertility of the soil in the experimental area, the high-yielding clover ploughed into the soil before rye sowing, the straw and crop residues not removed from the crop rotation fields. The yields of rye varied highly depending on the year and treatment. For the seven-year experiment period, the average yields for the organic and conventional treatments were 2.66 and 4.13 t ha^{-1}, respectively.

Table 2. The yield and quality of winter rye grown in the organically and conventionally managed crop rotations during 2008–2014

Properties	Treatment	2008	2009	2010	2011	2012	2013	2014	2008–2014
Yield	ORG	3.01	3.22	3.10	1.66	1.76	1.94	3.94	2.66
t ha^{-1}	CONV	4.52	5.14	3.98	3.56	2.96	4.67	4.09	4.13
Difference									1.47*
Protein	ORG	9.13	10.05	9.48	8.47	7.63	9.60	10.36	9.25
%	CONV	11.90	11.70	10.56	10.39	8.43	11.43	11.31	10.82
Difference									1.57*
1000 kernel weight	ORG	29.3	32.3	30.7	30.4	31.8	38.9	34.7	32.6
g	CONV	34.3	35.1	29.8	34.4	31.9	36.0	34.4	33.7
Difference									1.1 ns

ORG – organic without fertilizers, CONV – conventional with fertilizers and herbicides; * – difference is significant by LSD test at $P < 0.05$, ns – not significant

De Ponti et al. (2012), investigating the crop yield gaps between organic and conventional agriculture, have found that the yields of organically grown rye amounted to 76% (range 63–104%) of those obtained under conventional agriculture. As an average of our seven-year experiment, the rye yields of the organic treatment were 64% (range 42–96%) of those obtained for the conventional treatment. In 2011 and 2013, larger gaps in rye yields between the treatments were identified. This may be explained by the very harsh conditions in the winter months of 2010–2011 and 2012–2013. During both winters, deep snow covered unfrozen soil for a long period and a lot of rye plants, especially in the organic area, perished through different kinds of plant damage and this resulted in a severe decrease in yield.

The protein content of rye grains varied from 7.6% to 10.4% for the organic treatment, and from 8.4% to 11.9% for the conventional treatment. Due to the top-dressed nitrogen (N 34 + 34 kg ha^{-1}) as mineral fertilizer, the average protein content of the conventionally grown rye for the whole experimental period was significantly ($P < 0.05$) higher than that of the organically grown rye. In 2012, exceptionally low protein contents were registered for both treatments, caused by the unfavourable weather conditions during the rye growth period: cool and rainy days with no sunshine prevailed in June and July, slowing up the synthesis of protein and delaying the ripening of grains.

The 1000 kernel weight (TKW) is primarily dependent on the growth conditions and cultivar. Among the winter rye cultivars of the Baltic States, the cultivar 'Elvi' is characterized by low to moderate TKW – 31.8 g as the average of three-year experiments at Jõgeva, Estonia (Tupits, 2008). In our seven-year experiments, depending on the year and treatment, the TKW of this cultivar varied extensively (from 29 to 39 g). However, no significant ($P < 0.05$) differences in TKW between the treatments were found. The heaviest kernels (TKW 36–39 g) were produced in 2013 for both the treatments. This was the result of highly thinned vegetation caused by harsh winter and favourable weather conditions during rye growth and ripening. In addition, Tupits (2008) has demonstrated that rye plants on sparser plots are characterized by bigger kernels. According to Hansen et al. (2004), the kernel weight was negatively influenced by high temperature and drought during the ripening stage. In the summer months of 2010 and 2011, such weather conditions were prevalent, accounting for the lowest values of TKW during these harvest years.

The chemical analysis of mineral elements in rye grain showed that there were no significant differences in phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) contents between the organic and conventional treatments, or across experimental years. The dry matter (DM) of rye grains contained P 0.37–0.43%, K 0.40–0.51%, Ca 0.07–0.11% and Mg 0.10–0.13%. The average content of nitrogen (N) in grains of the conventional treatment was significantly ($P < 0.05$) higher than that for the organic treatment, being 1.73% and 1.48% DM, respectively.

Properties of rye flours. The basic technological parameters of flour include the content and quality of proteins, content of ash, amylolytic activity, expressed as falling number, and moisture (Sujka et al., 2017). Rye flours, in general, are characterized by somewhat lower protein content than wheat flours. In rye baking, the amount and quality of protein is not as important as in wheat baking. Rye proteins do not form a gluten network but they seem to be important during the dough mixing step, since they have some aggregation abilities and are surface active (Banu et al., 2011). Instead of gluten, the important quality factors for rye are the quality of starch and cell wall material, and the activities of endogenous enzymes modifying them (Ауэрман, 2003; Banu et al., 2011; Dvořákova et al., 2012). It is well known in the milling and baking industry that the quality of rye flour can highly differ between years because the amylases activity is significantly affected by the temperature and amount of rain during the growing season (Hansen et al., 2004; Banu, 2006). Annually changing rye raw material requires a re-evaluation of baking process parameters and/or using of flour improvers to guarantee the stable quality of baked products (Mikola, Viskari, 2012). In our study, the analyses of rye whole grain flours used for the baking tests showed that the protein contents for the organic treatment varied somewhat more than these for the conventional treatment (Table 3). For the organic treatment, the average protein content was significantly ($P < 0.05$) lower than that for the conventional treatment.

The ash content of cereal flours probably has no technological importance (Hansen et al., 2004; Sujka et al., 2017); however, it is important as a source of minerals needed for healthy diet. Because the majority of minerals are located in the outer layer of the kernel, the ash content of flour indicates how much of the outer layers have been included in the flour. Traditional Nordic rye breads are made of whole grain rye flour (ash content about 2%) where all of the components of the kernel are present (Rye and health, 2002, http://rye.vtt.fi/rye&health.pdf). The ash content of rye flours derived from the grain yields during our experiments in 2008–2014 was in the range of 1.6–2.1% DM and there were no significant differences between cultivation methods. It could be mentioned that the higher ash contents (1.9–2.1%) were registered for rye yielded in 2009 and 2014. This was probably caused by the fact that in these years, rye was grown in the crop rotation field No. 1 that adjoins a gravel road and the gravel dust might, to a certain extent, have polluted the developing grains.

Table 3. The properties of rye whole grain flours and breads depending on the cultivation methods

Properties	Treatment	Year of rye harvesting 2008	2009	2010	2011	2012	2013	2014	2008–2014
Properties of rye flour									
Protein %	ORG	8.26	10.71	8.20	8.12	8.81	7.87	10.80	8.97
	CONV	10.94	10.76	10.21	10.48	9.31	11.44	11.20	10.62
Difference									1.65*
Ash % DM	ORG	1.84	1.94	1.66	1.68	1.70	1.80	2.01	1.80
	CONV	1.57	2.08	1.73	1.60	1.94	1.62	2.09	1.80
Falling number, seconds	ORG	110	175	267	234	78	124	303	184
	CONV	120	175	268	172	62	72	289	165
Difference									19 ns
Starch % DM	ORG	62.9	62.5	66.8	66.5	63.2	64.1	65.2	64.5
	CONV	61.4	61.1	64.0	62.9	62.1	61.9	64.5	62.6
Difference									1.9*
Properties of bread									
Loaf volume cm^3	ORG	1464	1582	1459	1356	1393	1226	1345	1404
	CONV	1499	1552	1470	1410	1356	1099	1489	1411
Specific volume cm^3 g^{-1}	ORG	2.10	2.25	2.14	2.06	2.00	1.80	1.96	2.04
	CONV	2.10	2.16	2.16	2.10	1.99	1.59	2.11	2.03
Specific volume:protein	ORG	0.24	0.21	0.26	0.25	0.22	0.23	0.18	0.23
	CONV	0.24	0.20	0.21	0.20	0.21	0.14	0.19	0.20
Moisture %	ORG	47.8	49.8	48.1	47.9	47.5	50.0	49.0	48.6
	CONV	48.6	48.6	47.6	48.3	48.0	47.8	49.0	48.3
Acidity °	ORG	6.0	6.1	6.5	6.6	6.5	6.0	6.5	6.3
	CONV	6.0	6.6	6.4	6.3	6.5	6.5	6.2	6.4
Porosity %	ORG	55	57	60	53	45	59	49	54
	CONV	58	57	53	54	50	50	52	53

DM – dry matter; ORG – organic without fertilizers, CONV – conventional with fertilizers and herbicides; * – difference is significant by LSD test at $P < 0.05$, ns – not significant

The falling number offers useful information about the starch gelatinization phenomenon and the extent to which it is influenced by the amylolytic enzymes (Banu, 2006). Falling number determines the ability of dough to start and maintain fermentation process (Sujka et al., 2017). The amylases activity is easily measured by Hagberg falling number and it is known that decreasing falling number values cause the dough melting, which negatively affects the final bread shape and volume (Dvořákova et al., 2012). The activities of hydrolytic enzymes, especially amylase, are important factors that may limit the utilization of cereals. α-amylase is unique in modifying starch and its functional properties. In bread-making, some α-amylase is needed to sustain the production of sugars required for proper fermentation and consequent gas production (Hoog, 1969; Ауэрман, 2003; Basinskiene et al., 2011). However, excess α-amylase can have disastrous effects on bread quality (Basinskiene et al., 2011). β-amylase as an enzyme with sugar-producing character accelerates fermentation of the dough and improves the quality of the end product (Hoog, 1969; Ауэрман, 2003). Rainy periods in the ripening stage sometimes cause the pre-harvest sprouting of rye grains. In such cases, in parallel with the decreasing falling number, the activity of proteolytic and amylolytic enzymes in rye flour increases, which results in deteriorated rheological properties of dough and unsatisfying quality of baked product (Dojczew et al., 2004). Low falling number (under 100 sec) of flour made from sprouted grains is caused by the increased content of α-amylase. To decrease its amylolytic activity, the acidity of the dough needs to increase as well. This means that the dough will be prepared with leaven, which brings on the fast inactivation of α-amylase in the baking process (Ауэрман, 2003; Nowotna et al., 2006).

In our experiment, the falling number values of rye flour were distributed across a wide scale depending on the harvest years – varying by up to four times. The lowest falling number values (about 70 sec) of flours were recorded in 2012. This can most probably be explained by unfavourable growing conditions of the year: cool, cloudy and rainy periods lasted too long, delaying rye growth, as well as complicating the harvest. Although the falling number of rye flour for the conventional treatment showed much lower values than for the organic treatment in some years (2011 and 2013), the difference was not significant ($P < 0.05$) for the entire 7-year experimental period. However, Basinskiene et al. (2011), comparing enzymatic activity of cereals in different farming conditions, have found that the average α-amylase activity in organically grown rye was by 23% lower than that measured in conventionally grown rye samples, while the opposite trend was found for endoxylanase activity.

Starch is the major contributor to rye bread (Banu et al., 2011). Rye starches exhibit greater values of solubility in comparison to wheat. This is genetically influenced and connected to the higher enzymatic activity of rye compared to wheat. The high water binding capacity of rye starches is of great importance because starch binds water released during hydrolysis at the beginning of baking (Nowotna et al., 2006). Rye starch is also characterized by lower pasting temperature in comparison to wheat. It may be caused by the different crystallinity of wheat and rye starch granules, because the behaviour of starch in the water depends mostly on the internal structure of starch granules (Nowotna et al., 2006). Moreover, rye grain is characterized (in comparison to wheat) by the higher amount of dietary fibre, including fructans and ß-glucans, and by the highest pentosans content among all cereals. The presence of these carbohydrates contributes to the water binding capacity and viscosity of rye dough. Soluble pentosans, especially the ones with high molecular weight, cause the favourable properties of bread crumb and volume. The technological value of rye depends highly on its carbohydrate-amylolytical system (Nowotna et al., 2006).

In our experiment, the content of starch in whole grain rye flour for the organic treatment varied from 62.5% to 66.8% DM and that for the conventional treatment from 61.1% to 64.5% DM. The starch content for organically grown rye flour was significantly ($P < 0.05$) higher than for conventionally grown rye, as the average for the experiment period.

As is already well known for many grain crops, there is an inverse relationship between the concentration of starch and protein in seeds (Burešova et al., 2010; Seebauer et al., 2010; Tahir et al., 2011; Shen et al., 2016). Comparing the analysed data on rye flours of organic and conventional treatments, we found the inverse correlation ($r = -0.596$) between starch and protein content also for the rye flours (Table 3). When the protein content for the organic treatment was decreasing (as compared to the conventional treatment), the starch content was increasing. A strong negative relationship ($r = -0.981$) between protein and starch content in grains of most popular rye cultivars has also been demonstrated by Kunkulberga et al. (2017).

Water binding capacity of flour is one of the most important characteristics for the bread baking process. As is generally known, rye doughs often require a higher proportion of water than doughs in which wheat predominates. This could be explained by the higher bran content of rye flours, especially when milled from rye whole grain. The high water binding capacity of rye flour can also be explained by the higher content of water-soluble pentosans in rye grain compared to wheat grain (Ауэрман, 2003; Kalnina et al., 2015). In our experiment, the water absorption capacity of rye whole grain flour remained quite stable (147–152 ml per 100 g flour) and did not depend on the treatments or years. According to Hansen et al. (2004), the water absorption of rye whole grain meal is mostly influenced by genotype effects and less by harvest years.

Viscographic test of flours and properties of breads. Bread-making is a hydro-thermal process and therefore information on the temperature-dependent behaviour of the most important flour constituents is relevant for controlling the quality of the end product (Banu et al., 2011). Bread-making technology is based on the activity of various enzymes, of which the enzymes hydrolysing starch and proteins are of the biggest importance (Hoog, 1969).

Several systems (e.g., Mixolab, Brabender) are used to measure the evolution of the bread during the entire technological process, and to predict the quality of the baked products. While the falling number characterizes only the activity of α-amylase on the starch, the viscogram shows also the activity of other enzymes in the starch degrading process, which needs to be taken into consideration in the design of the technological process (Banu et al., 2011). The viscographic test of flour shows the behaviour of starch during the heating. Brabender Viscograph registers the temperature at the beginning of starch pasting and the maximal viscosity of starch paste.

The biochemical processes in flour and dough manifest themselves under the influence of various enzymes and microorganisms (primarily yeasts and lactic acid bacteria). In general, the enzymes act at temperatures of 0–70°C. However, their activity peaks at 35–50°C (Hoog, 1969). Different enzymes are characterized by different temperature-sensitivity. While α-amylase shows an optimal activity at 70–74°C, and tolerates heat of up to 97–98°C, β-amylase loses its activity at a much lower temperature (82–84°C) and shows optimal activity at 62–64°C (Hoog, 1969; Ауэрман, 2003). Depending on their origin, α- and β-amylases show differences also in pH. The pH optimum for α-amylase is 4.5 and it is inactivated at a pH below 4.0. In sourdoughs, the efficacy of α-amylase decreases. β-amylase is active across a much broader pH range, 4.5–9.2, with a pH optimum of 5.3 (Ауэрман, 2003; Bakery technology - Enzymes, www.classofoods.com/page1_7.html). Amylases convert starch into sugar. α-amylase splits the straight starch chains into smaller molecules (dextrins). α-amylase facilitates the formation of gas by the yeast in the dough and reduces the viscosity of the dough, thus helping it to rise. β-amylase splits maltose off the ends of the chains of the starch molecules. In dough, the sugar formed by β-amylase can be used by the yeast for fermentation and contributes to the browning of the baked goods. β-amylase cleaves maltose units from the non-reducing end of the starch molecule (Hoog, 1969; Mühlenchemie Glossary, www.muehlenchemie.de/english/know-how/glossary.html). In order for these enzymes to function, the starch granule must be ruptured so that the individual starch molecules are available for enzymatic action.

The viscographic analyses of the rye flours derived from the grain yields of years 2012, 2013 and 2014 were carried out by using Brabender Viscograph. As the content and activity of amylase enzymes was not investigated for the present research, we will interpret the viscograph readings only briefly, relying on the practical and literary knowledge. We will compare the viscograms of 2012 and 2014. In these years, the starch content of flours differed by about 2% (Table 3).

The starch gelatinization began at the same temperature (55°C) but the time to maximum viscosity was different (Table 4). In 2012, the maximum viscosity was reached after 27 and 24 min (for the organic and conventional treatments, respectively), whereas for the 2014 flour, it took 3–5 min longer. This could suggest that the activity of α-amylase on the degradation of starch granules was taking place at different temperatures. At the start of the cooling period, the loss of maximum viscosity was more than 5-fold for the 2012 flours, but only 2-fold for 2014. This might be due to different activity of α-amylases because the falling numbers of flours were drastically different (about 70 sec in 2012 and 300 sec in 2014 (Table 3). There were no significant differences in the loaf volumes. However, the higher activity of α-amylase (2012) was measurable in the bread porosity: the denser the bread crumb (the pores are compact), the lower porosity.

In 2013, extraordinarily weak viscographic results and low falling number (72 sec) of flour were proven for the conventional treatment. In this year, rye harvesting was delayed due to unfavourable harvest conditions. The grain of the conventional treatment lodged and might have been contaminated with soil and pathogenic fungi. As the pathogen *Fusarium* spp. destroys starch granules, storage proteins and cell walls, this subsequently affects the quality of dough properties (Papouškova et al., 2015). In 2013, for the conventional treatment, the bread volume was by far the smallest (only 1099 cm^3) among all the samples of the experimental period. Rye flour of such low quality seems to be suitable for bread-making only if mixed with wheat flour in accordance with the relevant dough recipe.

The viscograms of rye flours varied widely between the years and treatments. This is understandable because the flours and doughs are a living environment, containing various enzymes, yeasts, lactic acid bacteria, which work simultaneously and have very different mutual impacts and relationships.

If we compare the impacts of the organic and conventional treatments, then in spite of several fluctuations in the flour properties and viscograms, there were no significant differences in the properties of the end product as described in the average results for the seven-year experimental period. So, it might be concluded that by using the flours of organically grown rye and

Table 4. The results of viscographic analyses with flours of organically and conventionally grown rye

Point	Name	Organic			Conventional		
		time	torque of Brabender unit	temperature °C	time	torque of Brabender unit	temperature °C
				2012			
A	Beginning of gelatinization	00:17:15	41	55.4	00:16:55	49	54.7
B	Maximum viscosity	00:27:45	496	70.9	00:24:45	289	66.4
C	Start of holding period	00:42:00	113	92.1	00:42:00	33	92.1
D	Start of cooling period	00:57:05	88	92.5	00:57:00	26	92.5
E	End of cooling period	00:00:00	44	30.2	00:00:00	59	30.1
F	End of final holding period	01:25:40	225	50.2	01:25:40	75	50.1
				2013			
A	Beginning of gelatinization	00:16:40	45	54.4	00:00:05	1	30.2
B	Maximum viscosity	00:22:00	262	62.3	00:41:30	3	91.3
C	Start of holding period	00:42:00	25	92.0	00:42:00	2	92.0
D	Start of cooling period	00:57:00	21	92.5	00:57:00	2	92.5
E	End of cooling period	00:00:00	56	30.0	00:00:00	3	30.1
F	End of final holding period	01:25:40	63	50.1	01:25:40	2	50.0
				2014			
A	Beginning of gelatinization	00:16:30	51	54.2	00:17:20	39	55.4
B	Maximum viscosity	00:30:20	403	74.7	00:29:25	275	73.2
C	Start of holding period	00:42:00	231	92.1	00:42:00	245	92.1
D	Start of cooling period	00:57:00	219	92.5	00:57:00	138	92.5
E	End of cooling period	00:00:00	62	30.1	00:00:00	52	30.1
F	End of final holding period	01:25:40	510	50.0	01:25:40	330	50.1

conventionally (with the moderate input of synthetic fertilizers and herbicides) grown rye, we can produce the breads of the same quality.

Conclusions

1. The seven-year experiment on a sandy loam *Albic Stagnic Luvisol* showed that the yields of organically grown winter rye varied significantly (1.7–3.9 t ha^{-1}) across years, and remained, on the average, at 64% (range 42–96%) of those obtained under conventional (CONV) treatment.

2. The protein content in rye grains depended on the year and treatment, being significantly ($P < 0.05$) lower for the organic (ORG) treatment. No significant differences in the 1000 kernel weight and kernel chemical composition (P, K, Ca and Mg content) were established between the treatments.

3. The analyses of rye whole grain flour showed that the falling number and the ash content were not affected by cultivation methods; however, falling number varied significantly during the experimental years. The flour derived from organically cultivated rye was characterized by significantly ($P < 0.05$) higher starch content than the conventional flour. An inverse correlation ($r = -0.596$) was established between starch and protein contents in rye whole grain flour. The water binding capacity of flours was quite stable (147–152 ml per 100 g flour) for the all cases in our investigation.

4. The pasting behaviour of rye whole grain flours derived from yields of the last three years of our experiment, was investigated by using Brabender Viscograph. Due to several reasons (primarily the extremely different falling numbers of different years' flours), the viscographic results proved quite different and do not allow us to make reliable conclusions on the impact of the cultivation method on the rheological properties of the flour.

5. The results of baking tests demonstrated that the bread volume and quality properties of baked breads do not depend on the cultivation method of winter rye. It may therefore be concluded that breads produced from rye grown under organic farming and/or properly managed conventional farming by the means of sourdough fermentation are practically of the same quality.

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Ekologiškai ir tradiciškai augintų žieminių rugių produktyvumas, kokybė ir duonos kepamosios savybės

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Santrauka

Šiaurės Europoje rugiai ir kviečiai yra pagrindiniai duoniniai grūdai. Viso grūdo rugių produktai yra maistinių skaidulų šaltinis, juose taip pat yra keli bioaktyvūs junginiai, darantys teigiamą įtaką sveikatai. Dėl negausių rugių auginimo taikant skirtingas auginimo sistemas tyrimų trūksta informacijos apie jų įtaką ruginės duonos kokybės savybėms. Tyrimo tikslas – palyginti rugių ekologinį ir klasikinį auginimo būdus. Buvo tirtos šios jų savybės: grūdų derlius ir kokybė, viso grūdo ruginių miltų ir galutinio produkto savybės. Kepimo bandymai buvo atlikti naudojant raugo fermentaciją, o rugių tešlos savybės buvo įvertintos Brabenderio viskografu. Rugiai auginti penkių metų sėjomainoje smėlingame priemolyje, pajaurėjusiame stagniniame išplautžemyje (ID). Prieš rugių sėją į dirvą kaip žalioji trąša buvo įsėti raudonieji dobilai. Ekologinėje auginimo sistemoje cheminių produktų nebuvo naudota. Auginant įprastai rugiai buvo tręšti mineralinėmis trąšomis ($N_{83}P_{30}K_{75}$ kg ha^{-1}) ir naudoti herbicidai.
Septynerių metų trukmės eksperimento rezultatai parodė, kad rugių grūdų derlius, gautas juos auginant ekologiškai, buvo 64 % mažesnis, lyginant su augintais įprastai. Tradiciškai augintų rugių grūdų baltymų kiekis buvo esmingai ($P < 0,05$) didesnis nei augintų ekologiškai. Nustatyta atvirkštinė koreliacija ($r = -0,596$) tarp baltymų ir krakmolo kiekio viso grūdo rugių miltuose. Nors ekologiškai ir tradiciškai augintų rugių miltai skyrėsi keliomis savybėmis ir viskogramomis, esminių galutinio produkto (duonos) skirtumų tarp auginimo sistemų nebuvo nustatyta. Taigi galima daryti išvadą, kad duona, iškepta iš viso grūdo rugių, augintų ekologiškai ir tradiciškai, iš esmės buvo vienodos kokybės.

Reikšminiai žodžiai: baltymai, grūdų derlius, duonos kepalo tūris, krakmolas, kritimo skaičius, raugas.