Volume 66 40 Number 2, 2018
https://doi.org/10.11118/actaun201866020371

QUALITY AND YIELD OF *TRITICUM DURUM* UNDER TEMPERATE CONTINENTAL CLIMATE OF THE CZECH REPUBLIC

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Abstract

POLIŠENSKÁ IVANA, JIRSA ONDŘEJ, SPITZER TOMÁŠ, SEDLÁČKOVÁ IRENA, MÍŠA PETR. 2018. Quality and Yield of *Triticum Durum* Under Temperate Continental Climate of the Czech Republic. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, 66(2): 371–379.

In Europe, durum wheat is traditionally grown primarily in the Mediterranean region. A question arises as to whether now, in a situation of global climate change, the conditions for durum wheat might be more favourable also in countries with temperate continental climate. Field trials at a location in the south-eastern part of the Czech Republic with a typical European continental climate were established in four harvest years (2011–2014). Yield, quality and deoxynivalenol content were evaluated and the impact of year and variety was studied. The best quality was achieved in 2013, when 4 of 5 varieties met all the quality requirements for durum wheat according to Commission Regulation (EU) No. 1272/2009. The most frequent reason for unsatisfactory quality was loss of vitreousness and low falling number. In 2012, three varieties froze, and this year was therefore excluded from evaluation. Yield varied between 7.6 t ha^{-1} in 2013 to 10.9 t ha^{-1} in 2014 and it was in a negative, statistically significant relationship with most of qualitative traits, particularly with vitreousness (r = −0.72). The strongest correlation between qualitative traits was found between vitreousness and thousand kernel weight (r = −0.73) and vitreousness and test weight (r = 0.70).

Keywords: durum wheat, weather, technological quality, vitreousness, falling number, protein content, test weight, deoxynivalenol, yield

INTRODUCTION

Quality requirements for durum wheat for the purposes of intervention buying-in are defined in the EU by Commission Regulation (EU) No. 1272/2009 (European Union, 2009). Vitreousness (endosperm translucency) is an essential quality factor for durum wheat and it is related to the firmness of the starch-protein matrix. The proportion of vitreous grains should be at minimum 83 %. Bulk density, as measured by test weight (TW), should be at least 78 kg hl^{-1}. TW is known to be positively correlated with semolina yield within a wide TW range (Fabriani and Lintas, 1988). Other evaluated parameters include crude protein content in dry matter (CPC, min. 11.5 %); falling number (FN, min. 220 s); and ratio of admixtures and impurities (max. 12.0 %). It is necessary to take into consideration also contamination by *Fusarium* mycotoxins. Two of those, deoxynivalenol (DON) and zearalenone, are limited by Commission Regulation (EU) No. 1881/2006 (European Union, 2006). There is a higher limit for maximum DON content in *T. durum* grain (1,750 µg kg^{-1}) as compared to that in *T. aestivum* (1,250 µg kg^{-1}). Durum wheat is usually more susceptible to infection by *Fusarium* head blight and contamination with *Fusarium* mycotoxins than is *T. aestivum* if both are grown in similar conditions (Clear *et al.*, 2005).

Environment and potential interaction between environment and genotype are important factors influencing the quality parameters of durum wheat grain (Lerner *et al.*, 2004). Weather conditions have strong influence on the majority of quality traits in durum wheat. Moisture stress during grain filling can negatively affect grain quality by reducing TW, and grain vitreousness (Rharrabti *et al.*, 2003a).

Abad *et al.* (2004) reported variability in grain protein content according to growing season and location, and they also observed variability for other quality parameters such as gluten strength, vitreousness, and carotenoids content. Preharvest sprouting, connected with increased amylolytical activity, adversely affects FN, vitreous kernel content, and number of damaged kernels (Dick *et al.*, 1974). A general conclusion can be drawn that rainfall and temperatures during grain formation and ripening are critical for durum wheat quality (Garrido-Lestache *et al.*, 2005).

The aim of the present study was 1) to evaluate yield, quality and DON contamination of 5 durum wheat varieties grown in the climatic conditions of the south-eastern part of the Czech Republic, 2) to study impact of year and variety on the individual qualitative properties, and 3) to analyse relationships between quality traits and yield.

MATERIALS AND METHODS

Samples and agronomic conditions

Field experiments were carried out at a location Kroměříž (Czech Republic) during the four growing seasons 2010/2011 to 2013/2014. Kroměříž (49°16–17°N/17°21–22°E) is located within a sugar beet agricultural production area at an altitude of 235 m. Average annual temperature during the period 1971–2010 was 9.2 °C, and the average total annual precipitation is 576 mm. The soil is classified as silt loam Luvic Chernozem. Five winter type varieties of *T. durum* were included: four Austrian varieties (Saatzucht Donau GesmbH. and CoKG) – Auradur (year of registration – 2004), Logidur (2008), Lunadur (2006), Lupidur (2009), and one Slovak variety (ISTROPOL Solary a.s.) – IS Pentadur (2007).

The field trials were established as orthogonal randomized blocks with 6 replications. Varieties in individual blocks were arranged in rows, identically across years. The size of individual plots was 10 m^2. The experimental blocks were situated on the same field (large long-term crop rotation trial) in all years, but shifted to its different parts, and the crop succession was as follows: 1. spring barley, 2. lucerne (alfalfa), 3. lucerne (alfalfa), 4. durum wheat. The blocks were isolated from external environment by the bands (3 m) of soil sown by *T. durum.* Sowing dates are together with other important agronomical dates and crop protection measures (fungicidal treatment) summarised in Tab. I. Sowing rate was 4 million of germinating seeds per ha. Sowing rate and crop management practices were appropriate to the soil and climatic conditions in order to achieve good crop health and yield. Before sowing, 45 kg ha^{-1} of P_2O_5 (superphosphate 43%) and 125 kg ha^{-1} of K_2O (potassium salt 60%) were applied. Nitrogen was added in the form of potassium nitrate (27%) and so-called DAM (42.2% ammonium nitrate and 32.7% urea) to apply a total dose equal to 160 kg N ha^{-1}, split into regenerative, production, and qualitative applications. The trial plots were treated with growth regulators Retacel extra R 68 (chlormequat – chloride 720 g L^{-1}) at dose 1.5 L ha^{-1} (BBCH 30) and Moddus (250 g L^{-1} trinexapac-ethyl) at dose 0.3 L ha^{-1} (BBCH 31–32). Individual plots were harvested by small plot combine (Sampo SR 2010, SAMPO ROSENLEW, Ltd., Pori, Finland). Meteorological data (daily and monthly sum of rainfall, daily and monthly average temperatures, sunshine hours) were taken from an automated climate station of the Czech Hydrometeorological Institute located in the close vicinity (approx. 500 m) of the trial field (Fig. 1a,b). A more detailed course of weather for the period from the day of heading to harvest is documented in Tab. II.

Analytical methods

FN was determined according to EN ISO 3093:2009 (CEN, 2009a) using a LM 3120 mill (Perten Instruments, Stockholm, Sweden). CPC in dry matter was assessed by the Dumas combustion method according to ICC Standard No. 167 (ICC, 2009) using a FP-528 analyser (LECO Corporation, St. Joseph, MI, U.S.). Vitreousness was determined according to EN 15585:2008 (CEN, 2008) and is expressed as percentage of vitreous grains. TW was determined according to EN ISO 7971–3:2009 (CEN, 2009b). Concentration of the mycotoxin DON in grain was determined using an ELISA method (kit: Ridascreen, R-Biopharm AG, Darmstadt, Germany) with limit of quantification equal to 20 µg kg^{-1}.

Statistical analysis

The analytical data were reported as mean ± standard deviation of six replications. Because of compositional character of some data (Pawlowsky and Buccianti, 2011), protein, vitreousness, and DON were evaluated using the additive log-ratio transformation (alr). Normality of data was assessed using Shapiro-Wilk test. The data from each year and genotype were tested by a one-way ANOVA and those from the three years combined were analysed using the mixed-effect model, with a year included as a random effect. Statistical comparison of the means was made by post-ANOVA Tukey (HSD) test when significant main effects were detected. Correlations between the parameters were determined using the Pearson's correlation test. All calculations were performed using the STATISTICA Cz 12 software package (StatSoft, CR s.r.o). $p < 0.05$ was considered significant.

RESULTS

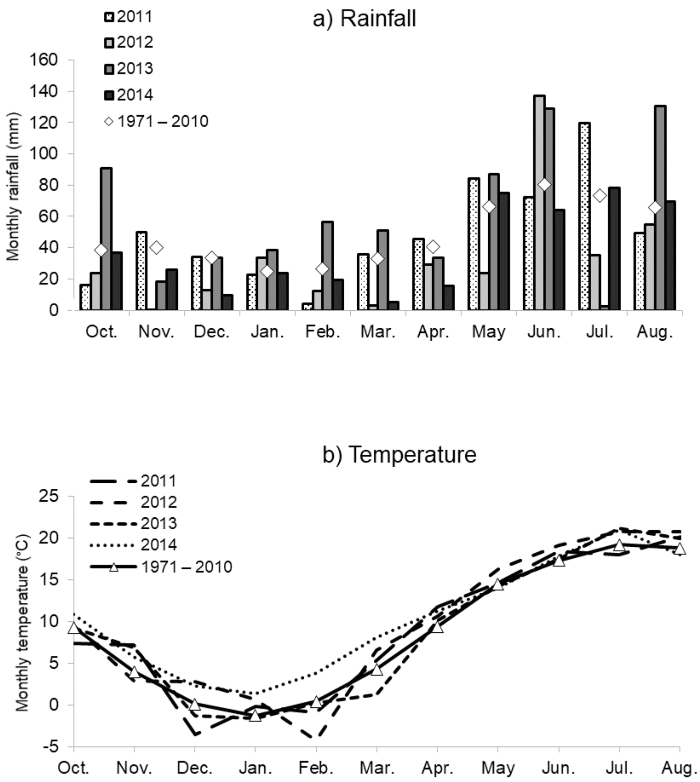
Quality, yield, and influence of year and variety

In 2011/2012, varieties IS Pentadur, Auradur and Lupidur did not regenerate in the spring. This year, the winter was exceptionally cold, with

I: *Important agronomical dates of field experiments*

Vegetation	Date of				Fungicide
season	**sowing**	**heading**	**maturity**	**harvest**	**treatment**
2010/11	7 Oct	25 May	2 Aug	4 Aug	14 Mar$^{1)}$, 9 May$^{2)}$, 3 Jun$^{3)}$
2012/13	11 Oct	30 May	28 Jul (4 Aug^{L})	1 Aug (8 Aug^{L})	16 May$^{2)}$, 7 Jun$^{3)}$
2013/14	2 Oct	20 May	14 Jul (17 Jul^{L})	3 Aug	25 Apr$^{2)}$, 20 May$^{3)}$

^{L} Lupidur $^{1)}$ Prosaro 250 EC 0.3 L ha^{-1} (prothioconazole 125 g L^{-1}, tebuconazole 125 g L^{-1}) + Fandango 200 EC 0.5 L ha^{-1} (100 g L^{-1} prothioconazole, 100 g L^{-1} fluoxastrobin)
$^{2)}$ Hutton 0.8 L ha^{-1} (spiroxamine 250 g L^{-1}, prothioconazole 100 g L^{-1}, tebuconazole 100 g L^{-1}) $^{3)}$ Prosaro 250 EC 0.75 L ha^{-1}



1: *Monthly sum of rainfall (a) and average temperatures (b) during vegetation periods in experimental years and comparison with long-term average (1971-2010), meteorological station Kroměříž, Czech Republic.*

II: *Weather conditions in given periods (10, 15, 20, 25, 30 days before harvest and in the period from heading to harvest) in harvest years 2011, 2013 and 2014, Kroměříž, Czech Republic.*

	2011				**2013**				**2013^{L}**				**2014**			
Days before harvest	**R (mm)**	**R.d.**	**S (h)**	**ΣT (°C)**	**R (mm)**	**R.d.**	**S (h)**	**ΣT (°C)**	**R (mm)**	**R.d.**	**S (h)**	**ΣT (°C)**	**R (mm)**	**R.d.**	**S (h)**	**ΣT (°C)**
from heading	226	37	490	4931	142	20	544	4504	170	21	633	5156	160	32	612	5229
30	107	18	190	563	3	6	323	641	30	4	332	673	76	17	237	645
25	107	17	137	459	2	5	269	538	30	3	285	576	74	15	191	533
20	96	15	89	349	2	4	210	438	30	3	233	475	67	11	164	443
15	93	12	48	254	2	3	166	344	30	3	170	367	65	9	105	327
10	32	9	31	173	2	3	110	236	29	2	113	247	19	6	63	214

L for variety Lupidur harvested 7 days later
R – sum of rainfall, R.d. – number of rainfall days, S – number of hours of sunshine, ΣT – sum of temperatures.

the average temperature for the month February −4.3 °C (long-term average: +0.4 °C), February daily temperatures in the first decade around −10 °C and minimum temperature reached −18.6 °C. There was no snow cover. Only varieties Logidur and Lunadur survived and were left for harvest, but their yield was significantly reduced (Logidur 2.7 t ha^{-1} and Lunadur 3.9 t ha^{-1}) in comparison with other years (Tab. VII). Therefore, results of the 2012 harvest were not included in the statistical processing and the trial was evaluated as the three-year.

The individual years differed significantly in all qualitative traits and also in DON content (Tab. III). For FN, no variety conformed to the demand at least 220 s in 2011 (the average 80 s), 4 varieties conformed in 2013 (247 s), and 1 variety in 2014 (154 s). For vitreousness, no variety was in conformance to demand at least 83 % vitreous kernels in both 2011 (the average proportion of vitreous kernels 50.4%), and 2014 (2.6%). In 2013, the average of vitreous kernels was 76.1% (Tab. III), and four out of five varieties complied. The only variety with lower vitreousness was Lupidur, which was harvested seven days later than the other varieties due to its mature delay. Moreover, the prolonged period of Lupidur maturation met with strong precipitation (28 mm) occurred 4 days before harvest. Thus, the proportion of vitreous kernels was only 23.8%.

Regarding TW, no variety conformed to the demand at the level of 78 kg hl^{-1} in 2014 (the average 75.4 kg hl^{-1}), three of five conformed in 2011 (the average 77.9 kg hl^{-1}), and in 2013, all varieties conformed (the average 81.3 kg hl^{-1}). The requirement to have CPC at least 11.5% was fulfilled for all years and varieties. The lowest CPC was achieved in 2011 (the average 12.6%), the highest in 2013 (14.2%). The effect of the year on all qualitative traits was the most important, but also the influence of variety and interaction between them were significant (Tab. IV).

The highest content of DON was performed in 2011 with mean amount 1,312 µg kg^{-1} that exceeded the maximum limit for DON content in case of Lupidur (2,095 µg kg^{-1}). In other years, the average DON content ranged from 222 µg kg^{-1} (2014) to 568 µg kg^{-1} (2013). The variation of DON content was significant in years and varieties, without significant interaction between these effects.

Grain yield reached in 2013 (7.6 t ha^{-1}) was significantly lower than both in 2014 (10.9 t ha^{-1}) and 2011 (10.7 t ha^{-1}). The variation of grain yield was significant in years, varieties and also significant interaction between these effects were proved.

Relationships between qualitative traits and yield

The strongest correlation between individual qualitative traits was found between vitreousness and TKW ($r = -0.73$) and vitreousness and TW ($r = 0.70$) (Tab. V). Other statistically highly significant ($p < 0.001$) correlations were found between FN and TW ($r = 0.62$), TW and TKW ($r = -0.62$), and TKW and FN ($r = -0.39$). DON had highly significant negative correlation with FN ($r = -0.42$) and TKW ($r = -0.34$). Yield was strongly correlated with all of analysed qualitative traits. Negatively with CPC ($r = -0.72$), FN ($r = -0.56$), vitreousness ($r = -0.50$), and TW ($r = -0.48$), positive correlation was found with TKW ($r = 0.64$).

Variety performance

For all varieties, the three-year average values of FN were lower than the required value (220 s), but there were significant differences between varieties. Lunadur and Lupidur had significantly lower three-year averages for FN than did the other 3 varieties (Tab. VI).

According to vitreousness, varieties split into three groups. The highest average vitreousness was found for Auradur, the lowest for IS Pentadur and Lupidur. The results of variety Lupidur are influenced by the fact, that in the year 2013 its harvest was postponed because it was not fully matured and it was harvested 7 days later than other varieties. In the interim, 4 days before harvest, precipitation of 28 mm fell during an afternoon storm and in addition to moistening spikes caused severe lodging of Lupidur trial plots. As a consequence, the vitreousness of variety Lupidur was reduced by 65.4% compared to the collective average of the other, earlier harvested varieties. A decrease neither in FN nor in CPC was observed, but there was substantial reduction in yield (Tab. VII).

Based on the CPC values, 4 statistically distinct groups were formed. The highest three-year average was found for variety Lunadur, on the subsequently lower level were varieties Lupidur and Auradur, folowed by variety Logidur and the lowest CPC was found for IS Pentadur. Logidur had the highest average TW value, on the contrary the lowest TW was found for Lupidur and Auradur. On the basis of TKW, varieties were divided into 4 groups. The highest three-year average was found for Lunadur, on the subsequently lower level was IS Pentadur and the lowest value was found for Auradur.

Contamination by DON was higher for Lupidur (mean value 1,106 µg kg^{-1}) and Auradur (832 µg kg^{-1}) than for IS Pentadur (381 µg kg^{-1}), Lunadur (560 µg kg^{-1}) and Logidur (624 µg kg^{-1}). Lupidur was the only variety exceeding the maximum limit for DON content, this was the case in 2011.

Concerning yield, IS Pentadur had the highest yield together with Logidur and Lunadur and they differed in a statistically significant manner from Lupidur. Yield of variety Lupidur was influenced by severe lodging due to its postponed harvest in 2013, when the yield of Lupidur was at the level of 72% of the average of other, earlier harvested varieties. In 2011 and 2014, the yield of Lupidur was at the level of 100% and 99.5% of the average of other varieties, respectively.

III: *Qualitative parameters and yield as mean values and standard deviations across five varieties of T. durum for three harvest years.*

Year	FN (s)			Vitreousness (%)			Protein (%, d.m.)			Test weight (kg hl^{-1})			TKW (g)			DON (μg kg^{-1})				Yield (t ha^{-1})		
	x		std	x		std	x		std	x		std	x		std	x	x*		std*	x		std
2011	80	c	11	50.4	b	7.9	12.6	c	0.4	77.9	b	1.3	44.4	b	1.9	1,312	7.0	a	0.5	10.7	a	0.7
2013	247	a	20	76.1	a	4.0	14.2	a	0.3	81.3	a	0.5	39.2	c	1.1	568	6.2	b	0.4	7.6	b	0.4
2014	154	b	12	2.6	c	1.1	13.1	b	0.3	75.4	c	0.6	50.3	a	0.5	222	5.2	c	0.3	10.9	a	0.3

FN – falling number, TKW – thousand-kernel weight, x – mean, std – standard deviation, * ln transformed values, ‡ minimum value possible by the method. Means with same letters are not significantly different (Tukey HSD, $p \geq 0.05$).

IV: *Two-way ANOVA of qualitative parameters of five T. durum varieties in harvest years 2011, 2013, and 2014. For DON, the ANOVA was performed using the ln-transformed data.*

Factor	DF	FN	Vitreousness	Protein	Test weight	TKW	DON	Yield
Year (Y)	2	728***	1,282***	201***	315***	491***	126***	396***
Cultivar (C)	4	16***	50***	59***	29***	129***	20***	14***
Y × C	8	57***	93***	36***	22***	11***	2	12***

FN – falling number, TKW – thousand-kernel weight, DF: degrees of freedom; F values, including the level of significance (* $p < 0.05$, ** $p < 0.01$, *** $p \leq 0.001$), are shown in the remaining columns.

V: *Correlation coefficients between qualitative and yield parameters, five T. durum varieties grown in harvest years 2011, 2013, and 2014 (n = 90).*

	FN	Vitreousness	CPC	TW	TKW	DON	Yield
FN	1.00						
Vitreousness	0.25*	1.00					
CPC	0.24*	0.29**	1.00				
TW	0.62***	0.70***	0.11 ns	1.00			
TKW	−0.39***	−0.73***	0.20 ns	−0.62***	1.00		
DON	−0.42***	0.33**	−0.10 ns	−0.03ns	−0.34***	1.00	
Yield	−0.56***	−0.50***	−0.72 ***	−0.48***	0.64 ***	−0.04 ns	1.00

*, **, *** significant differences at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively, ns – differences are not significant at $p \geq 0.05$, FN – falling number, CPC – crude protein content, TKW – thousand kernel weight, TW – test weight

VI: *Qualitative parameters and yield as mean values and standard deviations for five varieties of T. durum across harvest years 2011, 2013 and 2014*

Variety	FN (s)			Vitreousness (%)			Protein (%, d.m.)			Test weight (kg hl^{-1})			TKW (g)			DON (μg kg^{-1})				Yield (t ha^{-1})		
	x		std	x		std	x		std	x		std	x		std	x	x*		std*	x		std
IS Pentadur	175	a	19	36.7	c	2.0	12.5	d	0.3	78.6	b	0.5	45.2	b	0.9	381	5.6	b	0.4	10.3	a	0.5
Logidur	173	a	19	43.9	b	3.4	12.9	c	0.4	80.0	a	0.7	42.6	c	1.5	624	6.0	b	0.5	9.9	ab	0.4
Auradur	168	a	12	55.9	a	4.4	13.5	b	0.3	77.6	c	0.8	41.3	d	1.2	832	6.5	a	0.3	9.5	bc	0.4
Lunadur	138	b	11	47.3	b	4.1	14.0	a	0.2	77.8	bc	1.1	50.8	a	1.3	560	5.9	b	0.5	9.9	ab	0.5
Lupidur	148	b	11	31.4	c	7.8	13.6	b	0.3	77.1	c	0.9	43.2	c	0.9	1,106	6.7	a	0.3	9.1	c	0.5

FN – falling number, TKW – thousand-kernel weight, x – mean, std – standard deviation, * ln transformed values, ‡ minimum value possible by the method. Means with same letters are not significantly different (Tukey HSD, $p \geq 0.05$).

DISCUSSION

Vitreousness is an essential quality factor of durum wheat. Kernels with non-vitreous regions tend to reduce semolina yield (Wrigley and Batey, 2010) as more flour instead of semolina is produced during milling (Sissons, 2004). In our field trial, considerable variability in vitreousness between individual years was observed (2.6–76.1%) and although the harvest year had dominant influence on all of the analysed qualitative traits, the most affected among them was just vitreousness. A similarly substantial year dependence for durum

VII: *Qualitative parameters and yield as mean values and standard deviations for five varieties of T. durum grown in harvest years 2011, 2013 and 2014.*

Year	Variety	FN (s)			Vitreousness (%)			Protein (%, d.m.)			Test weight (kg hl^{-1})			TKW (g)			DON (µg kg^{-1})				Yield (t ha^{-1})		
		x		std	x		std	x		std	x		std	x		std	x	x*		std*	x		std
2011	IS Pentadur	116	a	25	21.4	c	3.4	12.0	c	0.4	78.4	ab	0.7	45.4	b	1.7	632	6.3	b	0.6	11.2	ab	0.7
	Logidur	97	a	27	40.8	b	7.6	12.2	c	0.4	79.3	a	1.3	42.5	bc	2.4	1,182	6.8	ab	0.9	10.4	ab	0.8
	Auradur	$62^{\ddagger}$	b	1	71.9	a	9.2	13.4	a	0.4	76.6	b	1.1	40.5	c	2.0	1,504	7.3	a	0.2	9.9	b	0.6
	Lunadur	$62^{\ddagger}$	b	0	50.8	b	8.0	13.1	ab	0.2	78.1	ab	1.7	52.1	a	1.6	1,146	7.0	ab	0.5	11.3	a	0.8
	Lupidur	$62^{\ddagger}$	b	0	67.3	a	11.1	12.5	bc	0.4	77.4	ab	1.7	41.7	c	2.0	2,095	7.5	a	0.5	10.7	ab	0.8
2013	IS Pentadur	238	b	19	87.9	a	2.0	14.1	c	0.2	82.0	b	0.5	40.1	b	0.5	420	6.0	b	0.2	8.5	a	0.3
	Logidur	308	a	22	86.8	a	1.1	12.9	d	0.4	83.7	a	0.3	36.2	c	1.6	564	6.3	ab	0.3	8.5	a	0.3
	Auradur	188	c	26	92.9	a	2.6	14.7	ab	0.3	78.8	c	0.9	35.0	c	0.8	661	6.4	ab	0.5	7.3	b	0.3
	Lunadur	258	b	19	89.2	a	3.7	14.5	bc	0.2	82.8	ab	0.4	43.4	a	2.1	364	5.8	b	0.6	8.0	a	0.4
	Lupidur	240	b	16	23.8	b	10.7	15.1	a	0.3	79.1	c	0.3	40.9	b	0.6	829	6.7	a	0.1	5.8	c	0.4
2014	IS Pentadur	170	b	14	0.7	c	0.6	11.6	d	0.3	75.5	b	0.3	50.1	b	0.6	90	4.5	c	0.3	11.2	a	0.4
	Logidur	114	d	9	4.2	a	1.5	13.6	b	0.3	77.1	a	0.4	49.2	c	0.4	128	4.8	bc	0.2	10.8	ab	0.3
	Auradur	252	a	9	3.1	ab	1.3	12.4	c	0.3	77.4	a	0.5	48.5	c	0.8	330	5.8	a	0.1	11.3	a	0.3
	Lunadur	94	d	13	2.1	bc	0.6	14.4	a	0.3	72.3	c	1.1	56.8	a	0.3	170	5.1	b	0.4	10.5	b	0.3
	Lupidur	142	c	18	3.1	ab	1.5	13.3	b	0.3	74.7	b	0.7	47.1	d	0.2	392	5.9	a	0.3	10.9	ab	0.2

FN – falling number, TKW – thousand-kernel weight, x – mean, std – standard deviation, * ln transformed values, ‡ minimum value possible by the method. Means with same letters are not significantly different (Tukey HSD, $p \geq 0.05$).

wheat vitreousness in conditions of Central Europe was observed also by Vida *et al.* (2002), who analysed a large set of genotypes and reported comparably wide deviation in the vitreousness values (3–100%). Durum wheat crop at the end of the grain filling period can lose its vitreousness if exposed to damp conditions. This is a severe problem for durum production in regions, where rain regularly occurs around harvest. This damage, however, seems to vary across varieties, regions and years (Dexter *et al.*, 1989; Sieber *et al.*, 2015) and further research is necessary, particularly with regard to stability of vitreousness under the influence of humidity. Among our experimental years, the best vitreousness was achieved in 2013, when in the heading-to-harvest period the precipitation sum and number of rainy days were the lowest and the sunshine duration the highest. The total precipitation sum in 30 days before harvest was 3 mm only. In other two harvest years, the vitreousness was much lower, particularly in 2014, varying only from 0.7% to 4.2% for individual varieties. Surprisingly, in 2011, when the sum of precipitation was higher and there were more precipitation days both in the whole period from heading to harvest and in all sub-periods of 30, 25, 20, 15, 10 days before harvest than in 2014, the vitreousness was better (from 21.4% to 67.3% for individual varieties). The cause of this discrepancy might be, that in 2014 the crop was exposed to repeated precipitation during the full maturity stage as there was a long gap between reaching full maturity and harvest. As was reported by Sandhu *et al.* (2009), even a short exposure (1–3 days) to high humidity when the grain is ready for harvest can cause a reduction in vitreousness. In our trial in 2014, fully matured grain was left in the field for 20 days and among them, 11 rainy days with total precipitation of 67 mm occurred. In 2011, full maturity was reached on 2 August and the crop was harvested on 4 August, so most of the precipitation fell on the crop before reaching full maturity.

Vitreousness of a durum wheat variety depends on the potential to form vitreous kernels and also to maintain this vitreousness under the influence of environment humidity (Sieber *et al.*, 2015). In our experiment, there were observed significant differences in vitreousness between varieties. Three statistically distinct groups were formed among 5 varieties included in our study, but the weather conditions in two of three harvest years were to such an extent adverse, that in individual harvest years either no variety was in conformance for vitreousness (2011 and 2014) or all complied (2013, with exception of later harvested Lupidur).

Associations between quality parameters are of great interest in defining optimal values of grain quality for a particular region and to help breeders to produce varieties with a good quality. In our study, vitreousness was negatively related to TKW (r = –0.73) and such association were also reported by Rharrabti *et al.* (2003b) and Bilgin *et al.* (2010). Higher temperatures and lower water availability during the grain filling season can be beneficial for vitreousness of the grain, but could lead to lower TKW. Between vitreousness and TW we found strong positive relationship (r = 0.70), the same as Debbouz *et al.* (1995) and Novaro *et al.* (1997). TW, similarly as vitreousness, is positively correlated with semolina yield (Fabriani and Lintas, 1988). Relationship between TW and TKW is controversially reported in the literature. While some authors stated that durum wheat samples with low TKW tend to have low TW (Dexter *et al.*, 1987; Dick and Matsuo 1988), Rharrabti *et al.* (2003b) and El-Khayat *et al.* (2006) reported a strong negative correlation, which is in agreement with our findings (r = –0.62). The reason for this ambiguity could be, that relationships between quality traits might be influenced by climatic conditions during grain filling and could depend on temperatures and water input during this phase (Rharrabti *et al.*, 2003b).

Both kernel vitreousness and protein content can significantly affect durum milling quality (Fu *et al.*, 2018). Vitreous kernels are high in protein content (Dexter *et al.*, 1989) and positive associations between protein content and vitreousness have been often reported (Rharrabti *et al.*, 2003a; Sissons, 2004; Bilgin *et al.*, 2010, Sieber *et al.*, 2015; Fu *et al.*, 2018). In agreement with previous studies, significant ($p < 0.01$) positive correlation was found also in our trial. According to Fu *et al.* (2018), vitreousness increases with higher protein content in the range of 9.5–12.5%, but this relationship is less evident in durum samples with high protein content (12.5–14.5%). This could explain our results, when correlation between vitreousness and CPC was weaker than e.g. between vitreousness and TW, as most of CPC values were higher than 12.5%.

Yield was in a negative, statistically significant relationship with most of the qualitative traits, mainly vitreousness (r = –0.72), FN (r = –0.56), CPC (r = –0.50), and TW (r = –0.48), while positive correlation was found between yield and TKW (r = 0.64). As reported by Borghi *et al.* (1997), vegetation seasons with weather conditions providing the opportunity for a good expression of quality parameters of durum wheat can cause a large fluctuation in yield.

The negative relationship between yield and CPC content is well known and for durum wheat was described in detail by Blanco *et al.* (2012). CPC was from the point of view of demand of Commission Regulation (EU) No. 1272/2009 (at least 11.5%) a non-problematic parameter and satisfactory CPC was achieved across all years and varieties. Although we found a negative relationship between yield and CPC, requirement on CPC content was fulfilled even in the high-yield year 2014 (in average 10.94 t ha^{-1}) with the mean CPC content at the level of 13.1% and also in 2011, when the yield reached 10.71 t ha^{-1} and the mean CPC content was 12.6 %. The negative relationship between yield and vitreousness was for durum wheat reported also e.g. by Korkut *et al.* (2007) and Bilgin *et al.* (2010) and it is a consequence of negative association between yield and CPC and positive association between CPC and vitreousness.

In the frame of all years, correlation between DON and FN proved to be negative and highly significant (r = −0.42). Precipitation during wheat flowering and onwards till the harvest can support head infection by *Fusarium* spp. and contamination of grain by mycotoxins (De Wolf *et al.*, 2003; Wegulo, 2012). Wet kind of weather near the harvest could lead also to increased amylolytical activity and lower FN (Wrigley and Batey, 2010). In our study, DON content was the highest in harvest year 2011, when limit for maximum DON content in *T. durum* grain at the level of 1,750 μg kg^{-1} was exceeded by variety Lupidur, having 2,095 μg kg^{-1}. It was the only case across all varieties and experimental years not falling below the limit given by Commission Regulation (EU) No. 1881/2006 at the level of 1,750 μg kg^{-1}. In 2011, the highest sum of precipitation was recorded in the period between heading to harvest and in addition to the highest DON contamination, the lowest FN was observed.

CONCLUSIONS

The most vulnerable quality trait in given environment seem to be vitreousness as rainfalls around harvest can cause its substantial irreversible loss. The risk, that satisfactory quality will not be achieved, could be reduced by carefully timed harvest, because the deteriorating effect of weather on quality was the worst in the stage of full grain maturity. Our results shown, that the conditions for durum wheat might be acceptably favourable also in countries not yet traditionally associated with growing this crop. It could be a new profitable opportunity for local farmers and not negligible would be contribution for increasing regional self-sufficiency.

Acknowledgements

This work was supported by the Ministry of Agriculture of the Czech Republic [Support for long-term conceptual development of research organization Agrotest Fyto, Ltd.].

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