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Breeding for improved technological quality in winter durum wheat

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Abstract. Under Hungarian conditions durum wheat must be capable of surviving several days of temperatures as low as –20°C without snow cover. Improving cold tolerance and technological quality simultaneously is no easy matter. The varieties used as sources of cold tolerance did not have satisfactory gluten strength and yellow pigment content, so high quality facultative durum wheat varieties were also included in the crossing programme. A period of ten years was required after gluten index measurements were commenced before over 70% of the new breeding lines had a gluten index significantly better than that of Parus, but since 2009 this proportion has been stable at over 80%. The gluten index of the majority of new winter durum wheat lines developed since the introduction of selection for gluten index is similar to that of high quality spring durum wheat genotypes. The other valuable technological quality trait of durum wheat is high yellow pigment content. The yellow index values of the advanced lines fluctuated over a wide range (17.7–32.2) in different years. Before selection was begun the average yellow index of these lines was 99.2% compared with that of the check variety Parus, while this value had risen to above 120% by 2006. The yellow index of the best lines exceeded that of Parus by 17.5–70.8% in different years.

Keywords. *Triticum turgidum* ssp. *durum*, – Gluten strength – Gluten index – Semolina colour – Yellow index.

Sélection pour l'amélioration de la qualité technologique du blé dur d'hiver

Résumé. *Dans les conditions de culture hongroises, le blé dur doit être capable de survivre plusieurs jours à des températures qui descendent même à -20°C sans couverture neigeuse. Améliorer à la fois la tolérance au froid et la qualité technologique n'est pas chose aisée. Les variétés utilisées comme sources de tolérance au froid n'ont pas une force du gluten et une teneur en pigment jaune satisfaisantes, donc des variétés de blé dur facultatives de haute qualité ont également été incluses dans le programme de croisement. Une période de dix ans a été nécessaire, après avoir commencé à mesurer l'indice de gluten, pour que plus de 70% des nouvelles lignées de sélection atteignent un indice de gluten significativement meilleur par rapport à celui de Parus, mais depuis 2009 cette proportion est restée stable à plus de 80%. L'indice de gluten de la majorité des nouvelles lignées de blé dur d'hiver développées depuis l'introduction de la sélection pour l'indice de gluten, est similaire à celui des génotypes de blé dur de printemps de haute qualité. L'autre caractère important de la qualité technologique du blé dur est la teneur en pigment jaune élevée. Les valeurs de l'indice de jaune des lignées avancées ont fluctué dans une large fourchette (de 17,7 à 32,2) sur différentes années. Avant d'entamer la sélection, l'indice de jaune moyen de ces lignes était 99,2% par rapport à celui de la variété Parus, alors que cette valeur a augmenté jusqu'à plus de 120% en 2006. L'indice de jaune des meilleures lignées a dépassé celui de Parus de 17.5-70,8% sur différentes années.*

Mots-clés. *Triticum turgidum ssp. durum – Force du gluten – Indice de gluten – Couleur de la semoule – Indice de jaune.*

I – Introduction

Winter durum wheat is mainly cultivated in the Eastern European countries. The most important producers of this crop are the former Soviet States (mainly Russia and Ukraine) but winter durum is also sown in other Eastern European countries (Bulgaria, Romania, Hungary, Slovakia, Serbia, Croatia, Macedonia) and in the Central Plateau of Turkey (Palamarchuk, 2005). Even breeding teams from the USA (Hall *et al*. 2011) and Canada (Tamburic-Ilincic *et al*., 2012) have recently released winter durum wheat varieties. The total production area of this crop is estimated at 1.2-

1.5 million hectares (Palamarchuk, 2005; EUROSTAT, 2013), which is about 8-10% of the spring durum wheat area. In Hungary it is cultivated on 8.5–14.9 thousand hectares (Hungarian Central Statistical Office, 2013).

Durum wheat generally has lower winter hardiness than bread wheat. However, in Hungary – due to the relatively short season for spring crops, often combined with drought stress during the spring period –winter durum is superior to the spring type. Under Hungarian conditions durum wheat often has to survive several days of temperatures as low as –20°C without snow cover, so the development of cold-tolerant varieties is a priority in breeding programmes.

The testing of the first winter durum wheat lines began in Martonvásár in 1982. These originated from the Odessa (Ukraine) breeding programme and had excellent cold tolerance and yielding ability, but their technological quality was poorer than that of spring durum wheat varieties. The genotypes first used as sources of cold tolerance had high protein content, but did not have satisfactory gluten strength and yellow pigment content. Later high quality facultative durum wheat varieties were also included in the crossing programme. The main objective of the Martonvásár durum wheat programme is to combine the high level of cold tolerance (also tested in phytotron chambers; Tischner *et al*., 1997) with strong gluten structure (measured by the gluten index test) and bright yellow colour (yellow index).

Gluten structure, including the strength of the matrix, is an important component of pasta quality (Cunin *et al.*, 1995). Gluten strength can be determined using several techniques. The laboratory equipment widely used for rheological measurements on bread wheat can also be used to analyse durum wheat samples (Sissons *et al.*, 2012). The determination of the gluten index (GI), based on the methodology elaborated by Perten (1990), is also a useful technique in durum wheat breeding programmes. A modified version of this method was first used for the analysis of durum wheat wholemeal and semolina samples by Cubbada *et al*. (1992). It is possible to perform the measurements even on wholemeal, and only 20 g samples are required for the analysis, so the method is particularly suitable in breeding programmes for analysing samples from early generations. The gluten index is a highly heritable, stable technological quality trait, mainly dependent on the genotype (Ames *et al*., 1999). In experiments performed by Clarke *et al*. (2000) the heritability of this trait in 120 progenies from three crossing combinations ranged from 0.84 to 0.93. Yellow pigment content is one of the most important technological quality parameters of semolina, the ground durum wheat product used in pasta-making (Irvine, 1971). The pigment, consisting mainly of lutein and esters of this compound (Lepage and Sims, 1968), has little or no influence on pasta-manufacturing and cooking properties (Dexter *et al*. 1981), but it leads to a considerable improvement in the aesthetic value, storability and marketability of pasta.

Yellow pigment content is a genetically determined trait (Braaten *et al.* 1962). Data in the literature suggest it is influenced chiefly by additive gene effects. The high heritability index of this trait also indicates that it is oligogenically inherited and determined by only a few alleles. Quantitative trait loci controlling the yellow pigment content (Elouafi *et al*., 2004; Patil *et al*., 2008; Zhang *et al*., 2008; Blanco *et al.*, 2011) and variation in the genes coding for key enzymes in carotenoid biosynthesis pathway (Cenci *et al*., 2004; Pozniak *et al*., 2007; Zhang and Dubcovsky, 2008) have been studied extensively.

Traditionally, total carotenoid content has been measured with a spectrophotometer (ICC Standard No. 152 and AACC International Method 14-60.01), but the yellow colour of the semolina can also be determined indirectly using a Minolta chromameter. In recent years this rapid method, which requires only small samples and no chemicals, has gained ground throughout the world (Borrelli *et al*. 1999). The Minolta b* index, known in the literature as the yellow index, is of most significance for the technological quality of durum wheat. This index is in very close correlation with the quantity of yellow pigment in the semolina. In experiments carried out by different research groups (Wehrle *et al.*,1997; Borrelli *et al.*,1999; Humphries *et al.*, 2004; Digesù *et al.*, 2009) the correlation coefficient between the two traits was found to be 0.88–0.95.

The present paper reports on the results achieved in improving the gluten strength and yellow index of winter durum wheat in the Martonvasar breeding programme.

II – Material and methods

The gluten index and yellow index of all the winter durum wheat varieties released from Martonvásár were tested in two replications in three consecutive years with contrasting weather conditions (2010 – extremely wet, 550.0 mm precipitation during the vegetation period; 2011 – dry, but high soil water content; 2012 extremely hot and dry, 202.5 mm precipitation).

Another analysis was made on data from experiments on advanced breeding lines to determine the effect of introducing tests on the gluten index and yellow index during the period 2000–2012. The number of lines included in the analysis ranged from 15 (2000) to 31 (2008–2012). Due to the nature of the experiment, the lines included in the analysis differed from year to year, so the data were compared with those of a check variety (Parus – a Ukrainian variety released in 1983; Palamarchuk, 2005), which was sown every year. The analyses were carried out in two replications.

Both experiments were set up on the same field in Martonvásár (47°18' N/18°49' E). According to the laboratory analysis of samples taken from the ploughed layer (1–20 cm) of the chernozem soil with forest residues, the soil of the selected area was sufficiently homogeneous. The topsoil, which contained no lime or damaging salts, had a weakly acidic pH and a loamy texture. Based on the humus content, it had moderate N supplies, while the AL-soluble values showed P contents close to the borderline between the good and very good categories (200 mg/kg) and good K supplies. With regard to microelements, the soil had a low Zn content, but good supplies of Cu.

Sowing was performed with HEGE-80 or HEGE-90 seed drills (Hans-Ulrich Hege GmbH und Co., Waldenburg, Germany) and in all the experiments the plant density was that recommended in Hungary (500 seed/m^2). The crop was protected against weeds and insect pests throughout the growing season, but no fungicide was applied. The plots were harvested at full maturity with a plot combine (Wintersteiger AG, Reid, Austria).

The gluten index of each winter durum wheat sample was determined from semolina on the basis of the ICC158 standard (ICC, 1995) using a Perten Glutomatic 2200 instrument and a Perten 2015 Centrifuge (Perten Instruments AB, Hägersten, Sweden). The yellow index of the winter durum wheat varieties and breeding lines was recorded using a Minolta CR-300 chromameter (Minolta Camera Co. Ltd., Osaka, Japan).

The semolina required for the analyses was prepared using a Brabender Junior laboratory mill (Brabender GmbH & Co. KG, Duisburg, Germany), converted as suggested by Vasiljevic *et al.* (1977). The removal of the bran and separation according to particle size were carried out on a Retsch sieve series (Retsch GmbH, Haan, Germany). The 160–315 µm fraction was further cleaned with a Chopin Semolina Purifier (Chopin Technologies, Villeneuve-la-Garenne, France). From 2010 onwards the durum wheat samples were ground using a Chopin CD2 laboratory mill, but the semolina was cleaned using the instrument described above, so the particle size of samples prepared before and after 2010 was the same.

III – Results

The gluten and yellow index values of the Martonvasar winter durum wheat varieties are presented in Table 1. The first varieties from the breeding programme were released in 1996. Weak gluten was characteristic primarily of older genotypes, because gluten strength was not included among the selection criteria when these varieties were developed. The main goal at that time was to improve adaptability, especially cold tolerance, in addition to which efforts had to be made to raise the yield potential to an acceptable level, since winter durum had to compete with winter wheat in their production zones (Dorofeev, 1987). Only when these aims had been achieved was it possible to turn attention to improvements in technological quality traits. This process is clearly illustrated by the gluten index values of winter durum wheat varieties bred in Martonvásár (Table 1).

Table 1. Gluten and yellow index of Martonvásár winter durum wheat varieties, 2010-2012.

Variety	Release Year	Gluten index 2010	Gluten index 2011	Gluten index 2012	Gluten index Mean	Yellow index 2010	Yellow index 2011	Yellow index 2012	Yellow index Mean
Odmadur 1*	1996	38.40	32.42	7.96	26.26	19.69	19.76	21.19	20.21
Odmadur 2*	1996	26.56	8.52	3.69	12.92	18.57	17.52	19.75	18.61
Martondur 1	1996	78.61	43.36	52.06	58.01	16.65	15.20	17.59	16.48
Martondur 2	1996	28.02	44.33	4.70	25.68	19.58	18.19	19.84	19.20
Martondur 3	1999	29.61	48.61	41.89	40.04	19.34	18.77	19.89	19.33
Mv Maxidur	2001	78.99	86.81	77.69	81.16	19.51	19.09	21.47	20.02
Mv Makaróni	2001	45.50	21.43	25.25	30.73	22.48	22.93	23.49	22.97
Mv Gyémánt	2004	72.69	56.53	4.94	44.72	22.56	18.26	20.14	20.32
Mv Hundur	2011	65.10	72.15	69.78	69.01	26.84	25.21	25.01	25.69
Mv Pennedur	2011	91.32	94.36	75.14	86.94	24.47	23.83	23.20	23.83
$LSD_{5\%}$		3.86	7.05	5.51	3.30	0.38	0.86	0.65	0.42

*Note: * Varieties bred jointly with the Plant Breeding and Genetics Institute Odessa, Ukraine.*

The Martonvásár durum wheat breeding programme was initiated in 1982, but right up to the mid-1990s selection was only made for kernel type and vitreousness. The use of instruments for analysis began in 1996, with measurements on the wet gluten content and the gluten and yellow indexes. The first four years of analysis were sufficient to demonstrate that there was great genetic variability both for gluten index and yellow index in the breeding material and that these technological parameters had little dependence on the year, thus making it possible to carry out efficient selection for stronger gluten and for brighter yellow semolina colour.

Improvements in the gluten and yellow indexes of the breeding lines had to be achieved while maintaining or improving the values of other traits (cold tolerance, protein content). The results achieved between 2000 and 2012 are presented in Figure 1. The gluten index of the lines referred to in the figure was significantly higher ($p = 0.05$) than that of Parus. In addition to the relative values, the figure also demonstrates the ratio of varieties in the given year with a gluten index classified in the ‘good to very good’ ($65 > GI \geq 85$) or ‘excellent’ (GI>85) categories given by Cubadda *et al.* (1992). A period of ten years was required after gluten index measurements were commenced before over 70% of the new breeding lines had a gluten index significantly better than that of Parus, but since 2009 this proportion has been stable at over 80%. The lines examined included a high proportion of genotypes with good-to-excellent gluten strength, so this trait no longer represents a bottleneck in the selection of advanced lines.

The mean yellow index values recorded for advanced breeding lines over the last thirteen years also confirm that the technological quality of winter durum wheat genotypes can be substantially improved by selection. The lowest value recorded in the laboratory was 17.70 (in 2001) and the highest 32.16 (in 2004). The yellow index values exhibited a wide range during the 13 years of investigations. The yellow index of the majority of the genotypes was close to average, but in each year it was possible to identify and select for winter durum advanced lines with an exceptionally high yellow pigment content, close to, or even higher than that of spring varieties.

As the result of selection there has been a substantial increase in the yellow index of winter durum wheat lines awaiting state registration. The data for the lines are compared with those of Parus, a Ukrainian winter durum variety with favourable agronomic traits, excellent winter hardiness and moderate yellow pigment content (Table 2). This variety has been sown as a control ever since the breeding programme was commenced. When selection was begun in 1996 the average yellow index of the lines compared with the control variety was 99.2%, while since 2006 this value is continuously above 120.0% (the largest difference was observed in 2009, when it was 142.8%).

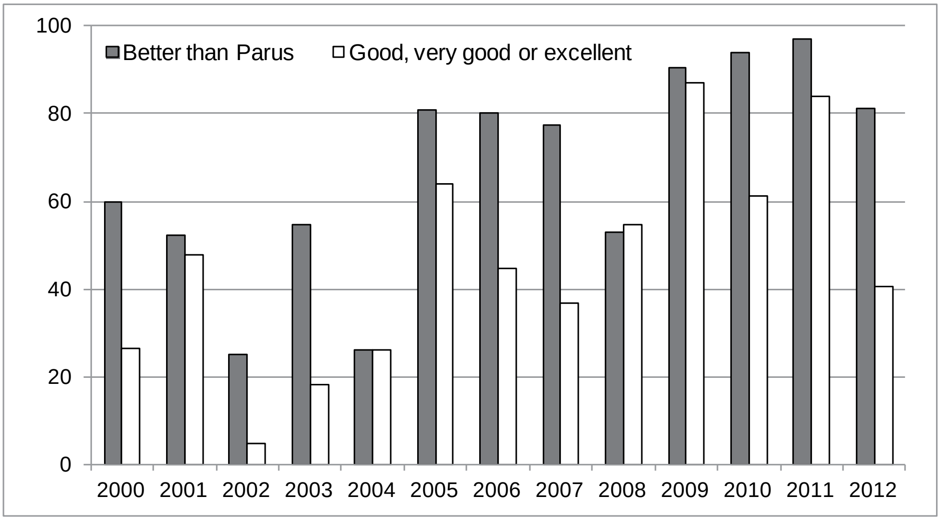

Figure 1. Ratio of Martonvásár winter durum wheat lines with a gluten index significantly better (p=0.05) than that of Parus, and with good-to-excellent gluten strength (gluten index>65). Martonvásár, 2000–2012.

Table 2. Yellow index of Parus and of Martonvásár winter durum wheat breeding lines, 2000–2012.

Year	No. of lines	Parus	Mv breeding lines			No. of lines		
			Min.	Max	Mean	> Parus	Medium quality*	High quality*
2000	15	20.64	20.06	27.04	23.09	11	9	6
2001	23	21.12	17.70	24.83	22.34	15	14	8
2002	20	24.06	22.94	28.84	25.15	12	6	14
2003	19	20.82	21.48	27.55	24.05	19	9	10
2004	22	23.67	25.32	32.16	27.21	22	0	22
2005	24	19.80	19.34	27.76	23.54	22	11	13
2006	28	20.65	20.61	31.24	26.41	27	3	25
2007	29	21.23	21.26	29.94	25.96	28	4	25
2008	31	20.68	22.10	29.08	25.59	31	2	29
2009	31	15.77	19.68	26.94	22.52	31	20	11
2010	31	18.56	20.55	26.84	23.80	31	13	18
2011	31	17.72	19.88	25.21	22.58	31	21	10
2012	31	17.73	19.14	25.08	22.80	31	21	10

** Classification according to Landi (1995). Medium quality: yellow index is between 19.0 and 23.5; High quality: yellow index is above 23.5.*

During the period 2000–2012 the yellow index of the best lines exceeded that of the check variety by 17.5 to 70.8%. Selection also led to a substantial reduction in the ratio of lines with a yellow index smaller than that of Parus. In the first year after the purchase of the Minolta CR-300 instrument (1996) this ratio was still 60%, while in 2003, after several years of selection, it had dropped to 0%. Since then, the majority of the lines (91.7–100.0%) have a yellow index significantly higher than that of Parus.

The gluten and yellow indexes are highly heritable traits in winter durum wheat, with little dependence on the environment. Both gluten index and yellow index measurements require small sample size, so these methods can be successfully used in winter durum breeding programmes for the improvement of gluten strength and yellow pigmentation. Using selection based on these parameters, the technological quality of winter durum wheat lines can be improved sufficiently to make them competitive with high quality spring varieties.

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References

AACC International, 2010. Approved Methods of Analysis, 11th Edition, Method 14-50.01. Determination of pigments. Final approval April 13, 1961; Reapproval November 3, 1999.

Ames N.P., Clarke J.M., Marchylo B.A., Dexter J.E., Woods S.M., 1999. Effect of environment and genotype on durum wheat gluten strength and pasta viscoelasticity. *Cereal Chemistry,* 76, pp. 582–586.

Blanco A., Colasuonno P., Gadaleta A., Mangini G., Schiavulli A., Simeone R., Digesù A.M., De Vita P., Mastrangelo A.M., Cattivelli L., 2011. Quantitative trait loci for yellow pigment concentration and individual carotenoid compounds in durum wheat. *J. Cereal Sci.* 54, pp. 255–264.

Borrelli G.M., Troccoli A.. Di Fonzo N., Fares C., 1999. Durum wheat lipoxygenase activity and other quality parameters that affect pasta color. *Cereal Chemistry,* 76, pp. 335–340.

Braaten M.O., Lebsock K.L., Sibbit L.D., 1962. Intergeneration relations of physical properties of dough and carotenoid pigment content in durum wheat. *Crop Sci.,* 2, pp. 277–281.

Cenci A., Somma S., Chantret N., Dubcovsky J., Blanco A., 2004. PCR identification of durum wheat BAC clones containing genes coding for carotenoid biosynthesis enzymes and their chromosome localization. *Genome,* 47, pp. 911–917.

Clarke J.M., Clarke F.R., McCaig T.N., Knox R.E., Ames N.P., 2000. Evaluation of predictors of quality for use in early generation selection. In: *Durum wheat improvement in the Mediterranean region: New challenges*. Royo C. *et al*. (eds.), *Options Méditerranéennes, Série A: Séminaires Méditerranéens* 40, pp. 439–446.

Cubadda R., Carcea M., Pasqui L.A., 1992. Suitability of the gluten index method for assessing gluten strength in durum wheat and semolina. *Cereal Foods World,* 37, pp. 866–869.

Cunin C., Handschin S., Walther P., Escher F., 1995. Structural changes of starch during cooking of durum wheat pasta. *Lebesmittel Wissenschaft und Technologie,* 28, pp. 323–328.

Dexter J.E., Matsuo R.R., Preston K.R., Kilborn R.H., 1981. Comparison of gluten strength, mixing properties, baking quality and spaghetti quality of some Canadian durum and common wheats. *Canadian Institute of Food Science and Technology J.,* 14, pp. 108–111.

Digesù A.M., Platani C., Cattivelli L., Mangini G., Blanco A., 2009: Genetic variability in yellow pigment components in cultivated and wild tetraploid wheats. *J. Cereal Sci.,* 50, pp. 210–218.

Dorofeev V.F., 1987. Pshenitsy mira. (Wheats of the World). *VO Agropromizdat*, Leningrad, pp. 560.

Elouafi I., Nachit M.M., Martin L.M., Hernandez P., 2001. Identification of a microsatellite on chromosome 7B showing a strong linkage with yellow pigment in durum wheat (*Triticum turgidum* L. var. *durum*). *Hereditas,* 135(2-3), pp. 255–261.

EUROSTAT, 2013. http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database. Consulted on May 16, 2013.

Hall M.D., Rohrer-Perkins W., Griffey C.A., Liu S.Y., Thomason W.E., Abaye A.O., Bullard-Schilling A., Gundrum P.G., Fanelli J.K., Chen J., Brooks W.S., Seago J.E., Will B.C., Hokanson E.G., Behl H.D., Pitman R.M., Kenner J.C., Vaughn M.E., Corbin R.A., Dunaway D.W., Lewis T.R., Starner D.E., Gulick S.A., Beahm B.R., Whitt D.L., Lafferty J.B., Hareland G.A., 2011. Registration of 'Snowglenn' winter durum wheat. *J. Plant Registrations,* 5(1), pp. 81–86.

Humphries J.M., Graham R.D., Mares D.J.. 2004. Application of reflectance colour measurement to the estimation of carotene and lutein content in wheat and triticale. *J. Cereal Sc.,* 40, pp. 151–159.

Hungarian Central Statistical Office, 2013. http://statinfo.ksh.hu/Statinfo/themeSelector.jsp?page=2&szst=OMN.

ICC (International Association of Cereal Science and Technology), 1990. Standard methods. Method No. 152: Determination of the yellow pigment content of durum wheat semolina and flour. Approved: 1990.

Irvine G.N., 1971. Durum wheat and pasta products. In: *Wheat Chemistry and Technology,* Pomeranz Y. (ed). AACC, St. Paul, USA, pp. 777-796

Landi A., 1995. Durum wheat, semolina and pasta quality characteristics for an Italian food company. In: *Durum wheat quality in the Mediterranean region.* Di Fonzo N. *et al*. (eds). *Options Méditerranéennes*: Série A. Séminaires Méditerranéens 22, pp. 33–42.

Lepage M., Sims P.A., 1968. Carotenoids of wheat flour: their identification and composition. *Cereal Chemistry,* 45, pp. 600–604.

Palamarchuk A., 2005. Selection strategies for traits relevant for winter and facultative durum wheat. In: *Durum wheat breeding: current approaches and future strategies.* Royo, C. *et al.* (eds). Food Products Press, New York, pp. 599–644

Patil R.M., Oak M.D., Tamhankar S.A., Sourdille P., Rao V.S., 2008. Mapping and validation of a major QTL for yellow pigment content on 7AL in durum wheat (*Triticum turgidum* L. ssp. *durum*). *Molecular Breeding,* 21, pp. 485–496.

Perten H., 1990. A rapid measurement of wet gluten quality by the gluten index method. *Cereal Foods World,* 35, pp. 401–402.

Pozniak C.J., Knox R.E., Clarke F.R., Clarke J.M., 2007. Identification of QTL and association of a phytoene synthase gene with endosperm colour in durum wheat. *Theor. Appl. Genet*., 114, pp. 525–537.

Sissons M., Abecassis J., Marchylo B., Cubbada R., 2012. Methods used to assess and predict quality of durum wheat, semolina and pasta. In: *Durum wheat: chemistry and technology.* Second Edition. Sissons M. *et al*. (eds), AACC International, Inc., St Paul, MN, USA, pp. 213–234.

Tamburic-Ilincic L., Smid A., Griffey C., 2012. OAC Amber winter durum wheat. *Canadian J. Plant Science,* 92, pp. 973–975.

Tischner T., Kőszegi B., Veisz O., 1997. Climatic programmes currently used most frequently in the Martonvásár phytotron. *Acta Agronomica Hungarica,* 45, pp. 85–104.

Vasiljevic S., Banasik O.J., Shuey W.C., 1977. A micro unit for producing durum semolina. *Cereal Chemistry,* 54, pp. 397-404.

Wehrle K., Seibel W., Gerstenkorn P., Kuhn M., 1997. Schnellmethoden zur qualitativen Beurteilung von Durumweizen. 2. Teil: Beziehung der Rohstoffeigenschaften Farbe und Protein zur Teigwarenqualität. *Getreide, Mehl und Brot.*, 51, pp. 73–78.

Zhang W., Chao S., Manthey F., Chicaiza O., Brevis J.C., Echenique V., Dubcovsky J., 2008. QTL analysis of pasta quality using a composite microsatellite and SNP map of durum wheat. *Theor. Appl. Genet.,* 117, pp. 1361–1377.

Zhang W., Dubcovsky J., 2008. Association between allelic variation at the Phytoene synthase 1 gene and yellow pigment content in the wheat grain. *Theor. Appl. Genet*., 116, pp. 635–645.