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BIOFORTIFICATION OF THE NUTRITIONAL VALUE OF FOODS FROM THE GRAIN OF *TRITICUM DURUM* DESF. BY AN AGROTECHNICAL METHOD: A SCIENTIFIC REVIEW

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Abstract

Enrichment of cereal grains is a priority area for research and an effective strategy compared to supplementation and food diversification. This paper discusses the current state of knowledge on the biofortification and nutritional value of food products from spring durum wheat grain, achieved by an agrotechnical method named ‘from field to table’ production. Biofortification refers to the production of safe food fortified with micronutrients and to the introduction of microorganisms that increase the bioretention of nutrients by plants, thus creating a new quality of food products as well as contributing to the protection of soil, perceived as a crucial resource in agricultural production. It is based on our knowledge of the physiology of yielding in conjunction with an increased productivity and higher value, essential in the context of health disorders due to dietary deficiencies. The choice of a durum wheat cultivation method depends on the crop’s habitat requirements, climate, proper selection of a previous crop, nutritional requirements, plant protection and storage. The conventional cultivation system diversifies the content of components, increasing Mn and Cu while decreasing P, K, Ca and Zn concentrations. Cultivation of this species on soil classified as very good wheat complex or good wheat ensures the highest yields characterised by high grain quality. This wheat is tolerant to water stress, although irrigation of spring durum wheat has been shown to improve nitrogen agronomic efficiency and to increase the yield of protein and energy. The recommended amount of nitrogen in plant fertilization is between 80-160 kg ha^{-1}. Durum wheat flour has a higher content of yellow pigments and better qualitative composition of gluten proteins, while its kernels have lighter and thinner hulls. Durum wheat flour absorbs less water during bread baking. Owing to this attribute, pasta from durum wheat is more adhesive to sauces, has compact texture and is more difficult to overcook.

Keywords: agrotechnology, fortification, durum wheat, grain quality, mineral components.

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INTRODUCTION

Contemporary agriculture is increasingly better at improving production efficiency and decreasing the costs of making foodstuffs. Simultaneously, people's diets are found to be deficient in nutrients. Attempts are made to counteract such deficiencies by providing the human population with vitamin or mineral fortified food products as well as dietary supplements. The issue of nutrient-deficient diets was the starting point for the following discussion of the current state of knowledge in this scope, with the purpose of raising consumer awareness as well as expanding the range of possibilities and uses of durum wheat products in a diet as natural substitutes of common wheat products that do not require fortification or supplementation. Moreover, production of new biological fertiliser components with micronutrients to be supplied under edible crops and the introduction of microorganisms able to improve the bioavailability of micronutrients by humans seem to create good opportunities for attaining high quality foods (Johns, Eyzaguirre 2007, Cakmak et al. 2010). The above solutions are termed as biofortification, a concept that has both advantages and disadvantages. Among its most significant benefits the following are worth mentioning: introduction of safe food enriched with micronutrients and use of microorganisms which increase the bioretention of nutrients by plants, thus creating a new quality of product and well as contributing to the protection of soil, an essential component in agriculture (Allen et al. 2006). Economically speaking, García-Bañuelos et al. (2014) claimed that genetic biofortification is the most efficient strategy for increasing the levels of Fe and Zn in a diet. Enrichment of cereal grains through plant breeding practice is a priority area in research and a successful strategy compared to supplementation and food diversification. On the other hand, the drawbacks of biofortifications include inferior biodiversity of species, impoverished diet, limited availability of grain produced by the above method to consumers, the need to design adequate technologies and machines to produce biofortified foods.

Advantages of durum wheat are well known and appreciated by nutritionists (Fagnano et al. 2012). The key factors in durum wheat agronomic practice are nitrogen fertilisation, plant density, plant protection treatments, preceding crop and tillage systems (Bassu et al. 2009, Panasiewicz et al. 2011, Spychaj et al. 2013). In the light of the relevant literature data, it has been assumed that differences in levels of the above factors are directly associated with controlling a production process (cultivation) and are responsible for some significant changes in the physical and chemical structure of grain. Hence, the way durum wheat is cultivated finds its direct manifestation in the nutritional value of food products made from durum wheat grain.

CULTIVATION

There is a steadily growing interest among producers and consumers in functional food based on the genetic resources of wheat grown about 6,000 years B.C. The most widespread species among the genus *Triticum* are *Triticum aestivum* ssp. *vulgare* – common wheat and *Triticum durum* Desf. – durum wheat (Carmichael, Kampouris 1975). Tetraploid durum wheat, mainly grown as a spring form, covers about 10% of the total acreage cropped with wheats of the genus *Triticum*. Globally, durum wheat is mainly cultivated in regions characterised by a dry and hot climate, typical of the Mediterranean countries, and the climatic zones with moderate weather during the plant growth and development period (Moragues et al. 2006). In the European Union, Italy is the major producer of durum wheat (3.6 mln t grain), followed by France (2.45 mln t), and next Greece and Spain (1 mln t each). It is essential to gain knowledge about durum wheat in terms of its agricultural and usability characteristics achieved under the soil and climatic conditions of a specific country because the range of productivity and geographical limits of genotypes are largely determined by the environmental factors (Segit, Szwed-Urbaś 2008). The promotion of data sharing among physiologists, pathologists, wheat quality scientists, national programme participants and breeders through linkages with gene banks will greatly stimulate the improvement of durum wheat with the aim to adapt this plant climate change worldwide (Lopes et al. 2015). In Poland, the total acreage of seed plantations has been expanding steadily: from 4 ha in 2012 to 8.9 ha in 2013 (The Research Centre for Cultivar Testing 2014). The spring form of durum wheat SMH87 is fully adapted to Poland's climate and its agrotechnology is similar to that of common wheat. A study by The Research Centre for Cultivar Testing (2014) conducted in 2011-2013 demonstrated that the spring variety of SMH87 had a three-year (2011-2013) average yield on the level of 70% of the model plant, irrespective of the level of agrotechnology. SMH87 is resistant to drought during the ripening stage (July/August). The awned variety is a sufficiently healthy plant, but relatively irresistant to lodging. Other characteristic traits are: high kernel hardness, good grain volume weight, high protein content in grain and high content of yellow pigments in grain.

ENVIRONMENTAL CONDITIONS

Durum wheat is a demanding crop with respect to soil, in which it resembles common wheat. It is also sensitive to temperatures and water conditions. Durum wheat is a relatively sturdy plant and contains more protein and gluten than common wheat (Woźniak 2006). It yields best when grown on soils classified as very good or good wheat complex, and is characterised by a high quality of grain. In the experiment run by Fagnano et al. (2012), durum wheat grown in conventional and organic farming on silty-clay loam developed from sand produced a moderately high yield. This species grows well in the temperature ranges of 3-4°C (min) to 30-32°C (max) (Briggle 1980). On the other hand, Bozzini (1988) observed durum wheat emergence at 2°C, but stated that the optimum temperature was 15°C. Temperatures over 35°C at the grain filling stage can alter the qualities of flour and dough (Blumenthal et al. 1993). With respect to the winter form of this wheat species, Salazar-Gutierrez et al. (2013) demonstrated that optimum temperatures expressed with the GDD index (Growth Degree Days) ranged within 1675-1844, 1017-1239 and 2827-2936°C for the respective phases: from sowing to tillering, from tillering to full ripeness, and from sowing to full ripeness. In turn, the water demand of durum wheat is 350-450 mm. However, there is a risk of an elevated quantity of mycotoxins in grain from regions with higher rainfalls (Fagnano et al. 2012). Under the damp weather conditions but a low total rainfall in July and a higher than average daily temperature, very high values of grain glassiness, hardness and falling number were obtained (Spychaj et al. 2011). Higher agronomic efficiency of nitrogen, and higher protein and energy yields (by 63% and 62%, respectively) were demonstrated when spring durum wheat had been irrigated (Panasiewicz et al. 2011). In the study by Dyńska et al. (2011), total protein content and wet gluten content in durum wheat grain were satisfactory only in one year of the research (i.e. 2003) with favourable weather conditions such as warm months with only periodic rainfall shortages. The effect of a climate in the region of origin on the agronomic performance of wheat cultivars was shown Royo et al. (2014). The climatic data from the main wheat-growing areas in each country of origin have led to the identification of four climatic zones in the Mediterranean Basin. Climatic zones accounted for 32.8, 28.3 and 14.5% of variance for days to anthesis, plant height, and grain filling rate, respectively. The number of days to heading and anthesis steadily increased when moving from the warmest and driest zone of origin to the coldest and wettest one. Additionally, landraces collected in the warmest and driest zone had smaller biomass, a lower chlorophyll content in the flag leaf, more fertile tillers, spikes and kernels m^{-2}, a lower grain filling rate, lighter grains, and lower yielding than those originating from colder and wetter zones. Landraces collected in countries with high solar radiation showed a shorter cycle until anthesis and smaller height and biomass accumulation, while higher temperatures after anthesis resulted in more tillers and spikes.

FERTILISATION

Another factor influencing the level of wheat yields and their quality is nitrogen fertilisation. Durum wheat has relatively high nutritional demands, which depend, among others, on the pool of available nutrients in soil and on the expected yield. A dose of nitrogen around 80-160 kg ha^{-1} and applied on 2-3 dates, i.e. pre-sowing, at the stem elongation phase and during the tillering phase, is recommended. In turn, phosphorus and potassium fertilisation should provide about 15-34 kg P ha^{-1} and 33-100 kg K ha^{-1} (The Research Centre for Cultivar Testing 2014). A field of durum wheat tested by Woźniak et al. (2014) was fertilised with nitrogen (in the amount of 120 kg ha^{-1}), phosphorus (34 kg P ha^{-1}) and potassium (83 kg K ha^{-1}). The total nitrogen dose was split as follows: 50 kg before sowing, 30 kg at the GS 22/23 phase (Zadoks et al. 1974), 20 kg at GS 32/33 and 20 kg ha^{-1} at GS 61/62. Panasiewicz et al. (2011) reported that different nitrogen fertilisation regimes resulted in a significant yield increase only when combined with the irrigation of spring durum wheat cv. Rusticano. Besides, under natural conditions (without irrigation), the yield of protein and energy increased significantly when a nitrogen fertilisation dose was increased up to 50 kg ha^{-1}. The results reported by Makowska et al (2008) indicate that nitrogen fertilisation has a distinct effect on grain physical characteristics such as hardness and vitreousness. It also influences the protein and wet gluten content in flour. However, no significant effect on the content of carotenoids and colour of pasta dough was observed. A similar, positive correlation between the gluten content and nitrogen fertilization was obtained Rachoń (1999). Woźniak and Gontarz (2011) demonstrated that a higher dose of nitrogen (150 kg ha^{-1}) than the standard one (90 kg ha^{-1}) increased the protein and gluten content in durum wheat grain, grain density and uniformity, glassiness, and total ash content.

ROBUSTNESS AND WEEDING

The volume of yield is also determined by the extend of plant infestation by fungal pathogens and weeds. To some extent, the severity of plant disease depends on plant genotypes and ambient conditions. Segit and Szwed-Urbaś (2008) showed a considerable degree of infection of the analysed durum wheat genotypes by powdery mildew and septoria glume blotch, and a small degree of infection by septoria. Out of 20 lines, 8 were nearly free from powdery mildew infection (values > 8.0). Also, less variation in the severity of ear infection by *Fusarium* was noted. Other studies have proven high resistance to wheat yellow dust (*Puccini astriiformis* sp. tritici) and brown rust (*Puccinia triticina* Erikss.) and moderate resistance to powdery mildew caused by fungi *Blumeria graminis* DC. f. sp. *tritici* Marchal (Matus et al. 2011). Durum wheat is less able to compete with weeds than common wheat (Kapeluszny et al. 2012), which was also confirmed by Buczek et al. (2014), Urban et al. 2011 and Haliniarz, Kapeluszny (2012). Plant diseases can reduce considerably grain yield and grain quality (Fernandez et al. 2010). Wang et al. (2002) showed that under a semi-arid environment, leaf-spotting diseases had only a small to no impact on test weight, kernel weight, grain yield or protein concentration. In order to control weeds and reduce fungal diseases of plants, it is inevitable to use chemical plant protection. RACHOŃ and SZUMIŁO (2009) analysed quality characteristics, i.e. grain test weight, grain uniformity and vitreousness, and concluded that there was a slight increase in these traits owing to complex plant protection. EL-METWALLY (2002) found that all weed control treatments significantly increased the crude protein percentage in wheat grain. In the study by MAY et al. (2014), fungicide application increased both grain and protein yield of durum wheat and the observed lower protein concentration was caused by dilution due to the higher yield. Fungicide applications must have facilitated a greater increase in carbohydrate deposition compared with protein deposition.

YIELD PRODUCTION

The spring durum wheat has lower yielding potential than common wheat, although new forms represent an increasingly better potential for yield production (MATUS et al. 2011). One reason might be that durum wheat has a much higher demand for water than common wheat (RHARRABTI et al. 2003, MATUS et al. 2011, KHALEDIAN et al. 2013), despite being tolerant to water stress (KHAYATNEZHAD 2012) and less response to the previous crop or cultivation system (WOŹNIAK et al. 2014). The cited authors have shown that the spring durum wheat cultivar called Duroflavus yielded higher in a conventional tillage system than under reduced tillage or in a cultivation system which included Roundup 360 SL. The conventional tillage system differentiated the content of nutrients, namely it increased the concentrations of Mn and Cu while decreasing the content of P, K, Ca and Zn. Moreover, pea grown for seeds proved to be a better preceding crop than oat or wheat (WOŹNIAK et al. 2014).

The grain yield is strictly connected with such yield components as the number of grain per ear, grain weight per ear and 1,000 grains weight (MATUS et al. 2011, SAYASLAN et al. 2012. Durum wheat is distinguished by a lower number of kernels in the ear, which can be compenstated for by a higher sowing density (SEGIT, SZWED-URBAŚ 2008). In a study by BASSU et al. (2009), the density per area unit of durum wheat plants grown in the Mediterranean Sea basin was 350 grains m^{-2}. In Poland, the spring durum wheat sowing density is 450 germinating grains of per m^2 (BUCZEK et al. 2014, WOŹNIAK et al. 2014). The tested densities of durum wheat, admittedly its winter form, ranging from 200, 350, 500 to 650 grains m^{-2}, have proven that yielding decreased at higher sowing densities (PANASIEWICZ et al. 2009). Moreover, a higher density of a wheat stand significantly decreased yield components such as the number of grains per ear and 1,000 grains weight. KHALEDIAN et al. (2013) demonstrated that a lower plant density per area unit had a more beneficial effect on the water use efficiency by plants during the growth and development. In turn, SULEWSKA et al. (2007) reported that spring durum wheat cultivars produced the highest yields at the density of 500 germinating kernels per m^2. The LAI value was the highest in the most dense sowing variant (600 grains m^{-2}). The sowing density also affected the protein content in dry matter of grains, which decreased from 15.2% to 14.8% as the sowing density increased.

HARVEST

Another significant aspect is the resistance of spring durum wheat plants to lodging before harvest and to pre-harvest sprouting. Apart from the weather conditions during harvest, this is largely a genotype-specific trait. MATUS et al. (2011) showed experimentally that spring durum wheat plants were variably tolerant to lodging (from low to high tolerance). This trait is significantly influenced by the plant height, stem flexibility and its strength, especially along the lower internodes (SADOWSKA et al. 2010). The knowledge of relationships between individual features is highly useful in the breeding of agricultural crops. It helps to determine how an increase in the value of one feature affects simultaneous changes in other features (WOJAS, GUT 2002, HOLLAND 2006). Lodging is accompanied by fouling (especially under excess moisture conditions). In a study by UKALSKI et al. (2008), both these traits were determined by genotypic factors rather than environmental conditions, which in the case of lodging mainly encompassed the mechanical properties of a stem. Evidence has been found that two analysed lines of winter common wheat with very elastic stems were highly resistant to lodging, scoring 7.2 and 7.3 on a 9-score scale, respectively. In turn, in a very old cereal such as spelt wheat, this trait was correlated with the resilience index, which means that plants are more resistant to deformations acting transversely on fibres, hence it can be expected that they would be more resistant to adverse external factors, e.g. forces of wind and rain (JAGODZIŃSKI 2005, SADOWSKA et al. 2010). A high stem resilience index value equated to a higher resistance to lodging. The morphological traits which were most decisive in terms of lodging resistance were the thickness of a stem wall, especially of the first and second internode. The analysed forms of barley resistant to lodging were distinguished by generally thicker straw, both the outer perimeter of stems and the thickness of their walls. However, the investigations by DOLIŃSKI et al. (1992) conducted on wheat provided contradictory results. The relationship between the resilience index and lodging tolerance was reverse. Apart from the specific mechanical structure of a stem, an application of a retardant shortens the stem, reduces the susceptibility to lodging and facilitates harvest.

Another question is the susceptibility of durum wheat to pre-harvest sprouting in correlation with lodging. Doliński et al. (2008) verified in their research that grain of *Triticum durum* Desf. was highly vulnerable to sprouting and only 2-5% of the analysed genotypes were resistant to this factor. Flour from sprouted durum wheat grain is unsuitable for the production of bread and pasta. Bread made from such flour has rubbery-sticky texture and a dark colored crust, whereas pasta crumbles during cooking. Flour obtained from sprouted grain has a high content of the enzyme α-amylase, which - at the time of sprouting and later during dough fermentation (pasta production) - results in the production of large amounts of undesirable monosaccharides and hydrolytic enzymes, e.g. lipases, prostheses, β-amylase and enzymes that catalyse the cleavage of α-1.6 linkages in amylopectin (Duffus, 1987).

The mechanical properties of grain are extremely important, for example when selecting an adequate harvest technology and a proper design of grain transport equipment. Good understanding of diffusion properties of grain is also essential for designing proper grain storage conditions (Zielińska et al. 2012, Markowski et al. 2013). The geometrical characteristics and texture of the grain surface, as well as technological processes are among the criteria used for correct classification and identification of cultivars. All these characteristics are taken into consideration in an assessment of the end product quality. Numerous studies confirm the need to continue research on the technological value of raw product as a function of the geometrical, physical and mechanical characteristics of grain, such as its size, shape, density, porosity, friction coefficient, strength and energy needed to achieve set deformation of grain under compression (Zielińska et al. 2012, Markowski et al. 2013).

NUTRITIONAL VALUE

High hardness of *Triticum durum* grain is dependent on the high energy consumption for grain fragmentation and the value of the Wheat Hardness Index (WHI) as well as a shorter fragmentation time, smaller quantity of produced flour and a lower Particle Size Index (PSI) compared to grain of soft wheat (common wheat grain) (Edwards 2010). Among different species belonging to the *Triticum* genus, durum wheat has the highest glassiness, while the lowest glassiness is attributed to the grain of the Polish wheat *Triticum polonicum* (among spring forms) and grain of spelt wheat *Triticum spelta* L. (among winter forms). Szwed-Urbaś (2009) showed that the endosperm of this grain is characterised by higher glassiness and hardness. Moreover, a close correlation has been demonstrated between the grain's glassiness and its density (Figiel et al. 2011). Spring lines of durum wheat possessing more glassy grain were characterised by higher hardiness and produced grains with a higher 1,000 grains weight as well as a higher protein and gluten content. In turn, the content of starch was lower, the compressive strength was high and the shear strength was lower. Despite the high content of gluten, durum wheat grain – compared to grains of common wheat and spelt wheat – was characterised by a low baking value, due to a low falling number and high dough softness (RACHOŃ et al. 2011).

Flour from durum wheat grain is called semolina, from the Italian word 'semola', meaning 'barn' or from the Latin word signifying 'flour'. Flour from durum wheat is different from common wheat flour in having a higher content of yellow pigments, a better quality composition of gluten proteins and the hulls that are lighter in colour and thinner (ISO 2008). Semolina is added to wheat bread flour, in which it improves the elasticity and yield of dough. With a 5% addition of semolina, the elasticity of dough increased to the value of 120 B.U.; additionally, the porosity and volume of dough also improved. However, a higher share of semolina (25 and 50%) in mixed wheat bread decreases the volume of baked bread compared to bread made from common wheat flour (SISSONS 2008). On the other hand, dough made from semolina is characterised by low elasticity (30 B.U.). In the research by CIOŁEK and MAKARSKA (2004), grain of durum wheat was characterised by higher concentrations of protein, wet gluten, higher glassiness and content of pigments (carotenoids) than bread wheat. These authors concluded that the content of protein and wet gluten, as well as the value of the Zeleny Index for spring durum wheat (the LGR 896/23 line) cultivated with a different contribution of this cereal in rotation systems, ranged from 14% to 15%, 32.2% to 35.9%, and from 40.7 ml to 58.3 ml, in three respective experiments. RACHOŃ and KULPA (2004) showed that durum wheat grain contained more total protein, wet gluten and ash than grain of common wheat. On the other hand, MIYAN et al. (2011) demonstrated that the protein content of durum was about 1% higher than in similar grain yields of bread wheat. Furthermore, the protein of durum wheat had a favourable composition of amino acids, especially a good content of albumines, globuline, tyrosine, lysine, methionine and phenylalanine (ISIDRO et al. 2008). NAZCO et al. (2014) focused on the glutenin composition used to estimate gluten strength, one of several quality attributes important for pasta cooking quality. However, all the durum wheat varieties registered in Bulgaria were characterised by the low yellow pigment content and the pasta produced from their flour did not preserve the colour as required by the current standards (PETROVA 2007). JARECKI et al. (2013) found out a decrease in the β-carotene content from 2.55 ppm achieved from a nitrogen-unfertilised treatment to 2.42 ppm after an application of 150 kg N ha^{-1}. An advantage of semolina is that it absorbs less water during bread baking than common wheat flour. Owing to this characteristic, pasta has a more compact structure, is more sticky to sauces and is less likely to be overcooked.

CONCLUSIONS

The problem of nutrient deficient diets was the starting point for the above review of literature, which discusses research undertaken for the sake of raising the share of hard durum food products in a diet as natural substitutes of common wheat products, which will not require fortification or enrichment. The nutritional values of durum wheat are well known and appreciated by nutritionists. Likewise, the habitat and agronomic requirements of this wheat are well recognized, but the yield of hard wheat, which is a product obtained from durum wheat plants, is the major production-limiting factor. Although hard wheat is characterised by high nutritional values, it has been relatively slowely incorporated into broad agricultural practice. One of the most serious obstacles, and the reason behind the above observation, is the fact that the yielding physiology of durum wheat remains largely unrecognised. Another drawback is the lack of universal agrotechnical guidelines for attaining a higher nutritional value of this plant, in particular the domestic cultivars of durum wheat.

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