Chapter 2
Triticale Breeding—Progress and Prospect

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Introduction

Triticale (×*Triticosecale* Wittmack) is a man-made cereal crop that can be synthesized by hybridizing wheat with rye (*Secale cereal*, *RR*). The first triticale was produced by Scottish botanist A. Stephen Wilson in 1875 when he succeeded in pollinating wheat with rye pollen (Wilson 1876). However, these triticale plants produced sterile pollen and hence could not produce viable offspring. It was not until embryo rescue techniques (Laibach 1925) and colchicine-induced chromosome doubling (Blakeslee and Avery 1937) were developed that the prospects for triticale breeding became viable (Oettler 2005). Simmonds (1976) summarized the various types of triticale that can be synthesized with different chromosomal constitutions. Crossing with different species of wheat, e.g., *Triticum turgidum* (AABB) or *Triticum aestivum* (AABBDD) will produce either hexaploid (AABBRR) or octoploid (AABBDDRR) triticale, respectively. Among the various types of triticale, hexaploid triticale (durum × rye) has been the most successful because of its superior vigor and reproductive stability. The octoploid type (common wheat × rye) suffers greater genetic instability and associated floret sterility (Mergoum et al. 2009). The original goal for producing triticale was to produce a new cereal crop that combined the superior agronomic performance and the end-use qualities of wheat with the stress tolerance (both biotic and abiotic) and adaptability of rye. Major efforts around the world have been undertaken to develop hexaploid triticale with improvements in agronomic characteristics, end-use quality, and resistance to various biotic and abiotic stresses. The first North American triticale

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breeding program was established in 1953 at the University of Manitoba in Winnipeg, Canada, to develop a high yielding, drought tolerant triticale for human consumption to be grown on marginal land. This effort resulted in Rosner, the first licensed spring triticale variety in Canada (Larter et al. 1970). Dr. N.E. Borlaug initiated the triticale research program at the International Maize and Wheat Improvement Center (CIMMYT) in Mexico in 1964 (Lelley 2006). By the early 1960s, hexaploid × octoploid crosses in Hungary resulted in several secondary triticale populations (T-30, T-57 and T-64) that were used to initiate the on-farm trials on sandy soils (Kiss 1966; Kiss and Kiss 1981). Two of these populations (T-57 and T-64) resulted in the world's first triticale cultivars released for commercial production (Zillinsky 1985). Based on annual repeated crossing and progeny testing, Kiss (1966) concluded that the hexaploid type was the optimum ploidy-level for triticale. Kiss established modern triticale breeding with the development of secondary hexaploids since they were as competitive on marginal soils as rye, with 30–50 % higher protein concentration. These advanced materials were transferred to Polish scientists who made tremendous progress in improving adaptation (mainly frost resistance). Since the 1990s, many triticale cultivars have been produced that have gained widespread popularity across Europe (Wolski and Tymieniecka 1988; Bona et al. 2002). As a man-made crop, triticale relies on the incorporation of new variability though the creation of new primary and secondary triticale populations using various wheat, rye, and triticale accessions. The genetic variability for important traits among various germplasm sources provides the foundation for further improvement to the crop. Through germplasm exchanges, the genetic resources developed at CIMMYT and other breeding programs have become an integral part of modern breeding programs.

Breeding Goals

Triticale can be used as grain for human food consumption and animal feed (mainly for pigs and poultry), as well as forage for livestock in the form of silage, fodder, grazing, and hay. In general, triticale combines the high yield potential of wheat with the biotic and abiotic stress tolerance of rye, making it more suitable for the production in marginal areas (acidic, saline, or soils with heavy metal toxicity). Despite having many advantages over wheat, global triticale production is still very low. In 2013, about 4 million hectares of triticale were grown worldwide with Poland, Belarus, Germany, France, and Russia being the major triticale producing countries (Table 2.1, FAO Stat). The low adoption of triticale is due to factors including production concerns, availability of end-use markets, production economics, policy, and competition from wheat. Among the production factors, susceptibility to diseases, such as ergot, *Fusarium* head blight (FHB), and leaf spots, poses major threats. Spring triticale cultivars are generally later maturing than wheat, which limits production in short growing season countries such as Canada. The volume weight of triticale cultivars has also been generally lower than wheat,

Table 2.1 Worldwide triticale area and production in 2013 (FAO statistics)

Country	Area harvested (ha)	Yield (kg/ha)
Australia	99,178	1726
Austria	44,996	4981
Belarus	441,630	2882
Belgium	6096	7050
Bosnia and Herzegovina	11,500	4073
Brazil	42,582	2865
Bulgaria	13,700	2825
Canada	11,400	2596
Chile	20,878	5574
China	210,000	2167
China, Mainland	210,000	2167
Croatia	14,087	3397
Czech Republic	46,816	4576
Denmark	13,300	5594
Estonia	3241	2724
France	385,022	5278
Germany	396,900	6573
Greece	8700	1149
Hungary	118,406	3873
Kyrgyzstan	721	1717
Latvia	14,100	2596
Lithuania	143,900	3135
Luxembourg	4561	5645
Mexico	3417	2917
The Netherlands	1953	5085
Poland	1,176,700	3631
Portugal	20,725	1559
Romania	72,529	3378
Russian Federation	241,108	2412
Serbia	38,961	4206
Slovakia	11,780	3352
Slovenia	3490	3622
Spain	140,900	2794
Sweden	22,889	4880
Switzerland	9159	5505
Tunisia	13,000	2008
Turkey	35,402	3333
United Kingdom	11,000	3500

although significant improvement has been made in the last decade. Poor end-use quality for human consumption relative to wheat has been a major hindrance to widespread adoption of the crop. Specifically, the protein concentration and gluten strength of triticale is lower than wheat, which contributes to poor bread-making quality. Hagberg falling number (FN), which is a common measurement of alpha–amylase-mediated starch damage, typically a result of sprouting, is extremely low for triticale compared with wheat. Triticale grain that is down-graded to feed classifications faces competition from lower grade wheat, which reduces economic returns to the producer. In some jurisdictions, triticale production is discouraged due to policies like lack of crop insurance coverage. Additional factors that contribute to low adoption of triticale may include limited research investment, lack of technology transfer, perception about triticale end-uses, lack of good-quality pedigreed seed, limited marketing options for farmers, and economic risks involved with triticale production.

To make triticale a successful crop, the primary objectives for improvement programs relate to lowering the production risks and costs of production, while increasing the economic returns per hectare. Production risks include losses due to various diseases and pests, and environmental factors such as weather-related damage [e.g., winterkill, lodging, shattering, late-maturity, and preharvest sprouting (PHS)]. The cost of production is influenced by weed competitiveness, water and nutrient use efficiency, and resistance to various abiotic stresses (e.g., salinity, acid soils, drought and heat). Ultimately, the returns per hectare are determined by the net yield (for both grain and biomass) and the price realized for the end-use quality offered to the marketplace. The numerous improvements that are required have directed long-term breeding objectives toward simultaneous improvement of agronomic performance, resistance to numerous biotic and abiotic stresses, and end-use quality characteristics. Among the agronomic traits, higher grain and biomass yield, plant height, reduced awn, enhanced straw strength, earlier maturity, higher volume weight, improved nutrient and water use efficiency, and tolerance to various stresses are of major concerns to producers. From a grain end-use quality standpoint, improvements in protein concentration and gluten strength (for bread-making quality), nutrient content, digestibility, and energy value (for livestock feed) are important considerations. For industrial applications, increases in grain starch content for bio-ethanol production, amylose content for bio-plastic production, and pentosans for glues are desirable. Enhancements in lignin and cellulose contents of the straw for uses in packaging materials and straw board could also be of value.

Breeding Strategies

The success of any breeding program depends on the availability of suitable germplasm with appropriate genetic variation for the traits of interest. Initially, the variability for traits in triticale has relied upon the production of primary triticale populations produced through intergeneric hybridization of common (AABBDD) or durum wheat (AABB) as a female parent and rye (RR) as a pollen parent (Mergoum et al. 2009). Since many of the octoploid triticales developed from bread wheat and rye are not genetically stable, most present-day genetic variation exists in hexaploid triticale. More recently, allelic variation from the wheat D genome contributed by *Triticum tauschii* has also been incorporated (Lukaszewski 2006). CIMMYT has been the predominant institution generating new primary triticales (Zillinsky 1985) and its international nursery program has been very successful in distributing this germplasm around the world. At some point, most breeding programs will create primary triticale to generate variability that cannot be found elsewhere; this has certainly been the case in breeding programs in Canada, Poland, and Hungary.

Triticale is a pre-dominantly self-pollinating crop with the possibility of some degree of cross-pollination. Hence for triticale, the breeding methods for self-pollinated crops could be applied (Lelley 2006), where the objective is to develop homozygous lines from populations resulting from the hybridization of two or more parents. Breeding objectives will dictate the choice of parental lines, the number of parent lines in the final cross, minimum population size in each generation, and selection strategies. The mode of inheritance, heritability, and the number of genes controlling the traits under consideration will impact how populations are handled and when selection for various traits should commence.

For cultivar development purposes, most single crosses are made with elite by elite parents (often registered cultivars) with complementary traits in order to combine desirable alleles from both parents. Some breeding programs include three or more lines in three-way or complex crosses to incorporate all of the desired traits. Designing three-way crosses with three parents {(A × B) × C)} may need special attention as the order of parental lines in a cross would determine the proportion of genetic makeup of each parent in the progeny. When designing complex crosses, careful forethought is required to ensure that the most desirable parent is top-crossed to the appropriate F_1 plants. Generally, parental lines with fewer desirable traits are crossed first and these F_1 plants are crosses to more desirable parents. In some circumstances, phenotypic and/or genotypic selection using DNA markers may be applied to complex F_1 plants before crossing to increase the probability that genes of interest will be present in the final population. Following completion of the desired crosses, various breeding methods can be employed depending on the availability of resources. The majority of triticale breeding programs use pedigree, bulk, backcross, and doubled haploid methods (alone or in combination) that are modified to take advantage of selection environments. The CIMMYT triticale program utilizes a modified pedigree selection method known as shuttle breeding where selection in successive early generations is performed in contrasting environments (Borlaug 1968). When lines are sufficiently homozygous, they are distributed globally for agronomic evaluation. This approach has been a major factor in CIMMYT's success in developing high yielding, widely adapted cultivars in a relatively short time (Mergoum et al. 2009).

Many triticale breeding programs utilize a modified bulk approach during the segregating generations, first used by Nilsson Ehle in 1908. This is the method of choice for the triticale breeding program at the Agriculture and Agri-Food Canada, Lethbridge Research Centre. In the early generations, selection is performed for qualitative traits such as plant height, maturity and disease resistance but selected individuals are harvested as bulk. In the F_5 generation, selected heads from the bulk populations are planted as head rows in a contra-season nursery in New Zealand. Selection is performed on F_6 rows based on plant height, resistance to lodging, maturity, and plant type. These lines are evaluated in preliminary and advanced agronomic trials over the next two to three years. Lines that display improvements over the existing check cultivars are advanced into cultivar registration trials.

Backcrossing, while effective in transferring a single trait into a cultivar, is rarely used in triticale breeding because simultaneous improvements are required for multiple traits. Agriculture and Agri-Food Canada successfully transferred a blue aleurone trait from wheat into AC Alta triticale using four backcrosses (Graf personal communication). The blue aleurone layer conferred a blue seed color to the grain and was an ideal candidate for backcrossing because it was monogenic, dominant, and exhibits xenia. Lines developed were used to study outcrossing rates in spring triticale (Hills et al. 2007).

In recent years, doubled haploid methods are being utilized in triticale breeding to achieve homozygosity rapidly. The use of doubled haploidy can reduce the cultivar development time by up to 4 or 5 years. This is particularly important in winter triticale, where only one generation per year is possible due to the requirement for vernalization. In addition, the use of doubled haploids can increase selection efficiency through the expression of recessive alleles in completely homozygous lines. Among the various methods for producing doubled haploid triticale plants, isolated microspore culture (IMC) and anther culture have been used successfully in Australia, Canada, Denmark, and Germany. In Canada, the first doubled haploid triticale cultivar T225, (Fig. 2.1) developed using IMC, was supported for registration in 2014 (Randhawa 2014).

Regardless of the breeding method used, desired results will only be achieved if effective selection strategies are employed. During the early segregating generations (F_2–F_4), selection should be performed on every generation for easily measured qualitative traits with simple inheritance and/or high heritability. These traits include resistance to diseases, plant height, days to heading and maturity, and plant type. To facilitate the expression of the traits of interest, various biotic and abiotic stresses are induced either naturally or artificially by the breeder. Natural abiotic stresses may include winter hardiness, soil pH, drought, and heat tolerance. Biotic stresses related to various diseases can be induced by creating epiphytotic conditions conducive to various pathogens. Lelley (2006) cautioned against the use of early generation selection in triticale segregating populations until a certain balance between wheat and rye is restored as the cross between two triticale lines will more or less affect the delicate genetic balance of the wheat and rye components, established through selection in the pure lines. Further triticale, even considered as a self-pollinating crop, may outcross and interfere with the development of pure lines

Fig. 2.1 Breeder seed rows of doubled haploid spring triticale T225 produced via isolated microspore culture by Agriculture and Agri-Food Canada, Lethbridge Research Centre

as outcrossing in triticale could reach up to 60 % (Lelley 2006) suggesting that the selection should be delayed until later generations. Selection for complex quantitative traits such as yield, agronomic adaptability, end-use quality, and some diseases with multigenic inheritance (e.g., *Fusarium* head blight) is generally delayed until F_6 or later generations when there is sufficient seed to conduct replicated trials or destructive end-use quality analysis. Following a few years of replicated testing at multiple locations with appropriate check cultivars, new candidates worthy of release may be discovered.

(a) **Agronomic traits**

Breeding for agronomic traits including grain and biomass yield, plant height, maturity, and straw strength are among the most important factors for maximizing economic return in triticale. The major components associated with triticale yield are grain and straw yield, harvest index, tillers per plant, number of seeds per spike, volume weight, and seed mass. Early triticale cultivars were low yielding, tall, susceptible to lodging and PHS, and had poor physical grain quality. Breeding efforts have resulted in significant improvements in grain yield and straw strength and reductions in plant height over the last few decades (Oettler 2005). New triticale cultivars often have grain yield that is significantly higher than wheat cultivars. In his review, Blum (2014) summarized the advances in triticale yield potential and stated that the CIMMYT international triticale yield nurseries (ITYN) were important instruments for studying progress in breeding and the adaptation of new germplasm. Analysis of these nurseries (Fox et al. 1990) indicated a yield improvement from ITYN 8 to ITYN 14, as well as an expected genotype by environment interaction for adaptation on a regional and global scale. A later study

(Josephides 1993) over 23 environments in Cyprus indicated that triticale performed as well as common wheat and better than durum wheat and barley. However, the latter two species performed better than triticale under late season drought stress. This observation was corroborated through the analysis of various CIMMYT international triticale nurseries (Reynolds et al. 2002, 2004). On average, triticale had the highest biomass and grain yield but had lower grain yield than common and durum wheat when conditions from spike emergence onward were sunny and warm. Spring triticale yield trials in western Canada have revealed up to a 10 % yield advantage over wheat (Randhawa 2015). Conversely, a recent study by Motzo et al. (2013), comparing yields of triticale and durum wheat, did not find greater yield reductions in triticale due to late season water deficit. It is therefore plausible that some triticale germplasm may suffer a reduction in fertility during sub-optimal conditions at anthesis. The potential advantage of triticale over wheat in biomass and grain yield was confirmed in a later study in Spain (Estrada-Campuzano et al. 2012). The higher biomass and yield potential of triticale in that study was explained by superior radiation-use efficiency (RUE) derived from greater sunlight interception by the triticale canopy as compared to wheat. This explanation is somewhat difficult to accept unless clearly linked to a unique canopy structure. However, improved RUE can also result from canopy function rather than radiation interception. Small grain variety tests in Hungary also revealed that triticale had a yield advantage over wheat, particularly in dry years and in marginal agricultural areas where triticale production was concentrated (Bona 2004). Further increases in yield potential will require improvements in harvest index by increasing nutrient response, straw strength, and better photosynthate partitioning.

The reduced awns in triticale is an important characteristic for conserved forage and grazing uses as rough awns poses a problem for feeding as a dried fodder (Salmon et al. 1996). The development of triticale with reduced awn expression was started in 1983 at the Field Crop Development Centre, Lacombe, Alberta, Canada. Spring wheat germplasm line RL4137 was used to incorporate both reduced awn characteristic and sprouting resistance into spring and winter triticale. A reduced awn characteristic line 88DL01 was developed using backcrossing several times to develop Bobcat winter triticale (Salmon et al. 1996). This line was subsequently used to develop other triticale cultivars such as Luoma and Metzger (winter type) and Bunker, Tyndal, and Taza (spring type). Both Bobcat and Metzger also have improved FN over check cultivar Pika.

(b) **Biotic and Abiotic Stresses Resistance**

To reduce production risk from various biotic and abiotic stresses, triticale breeding programs have incorporated various forms of resistance. In general, triticale has good levels of resistance to various diseases. However, *Fusarium* head blight, ergot, and leaf spots are of concern, as they can cause significant economic losses. The most serious problem associated with *Fusarium* head blight is the contamination of grains with mycotoxins, particularly deoxynivalenol (DON), which can render the grain unsuitable for human and livestock consumption. Breeding for resistance against FHB is one of the most effective methods to reduce the risk associated with this disease (Anderson 2007). Typical for this disease based on experience in other cereals, resistance is multigenic and its expression is highly influenced by environmental factors. Screening of 1375 germplasm accessions (Fig. 2.2) resulted in the identification of very few lines with good levels of Type II (resistance to fungal spread) and other forms of resistance (Langevin et al. 2009; Randhawa et al. 2013). Most of these lines showed a very high level of susceptibility compared with the spring triticale cultivar Pronghorn which expresses intermediate resistance. Despite low infection level, some of the lines showed higher level of DON content which showed triticale is more sensitive to DON accumulation than wheat. Langevin et al. (2009) speculated that the higher DON content may be due to a more fragile pericarp during the initial development of the triticale seed. Research is underway to identify quantitative trait loci (QTL) that confer resistance to FHB.

Ergot continues to be an important disease concern in triticale. Associated with floret sterility, susceptibility to this disease was a major limitation to triticale expansion in the past (Mergoum et al. 2009). Ergot sclerotia (bodies) contain compounds that are particularly toxic to humans and monogastric livestock, and when in sufficient numbers can render the grain unusable. Removal of the ergot bodies or blending with uncontaminated grain is the only remedial step that can be taken. Triticale has sufficient genetic variation (Fig. 2.3) for tolerance to this disease (Randhawa et al. 2013) and good progress has been made in developing cultivars with improved resistance (McLeod et al. 2012; Beres et al. 2012; Randhawa 2014). Resistance has also been identified in the CIMMYT durum line Green 27 (Menzies 2004) and efforts are underway to transfer this resistance to triticale.

Leaf spots disease including *Septoria tritici* blotch and *Stagonospora nodorum* blotch can cause economic damage in triticale. The distribution of these pathogens varies in different countries and problem could be more severe if triticale is grown on field after wheat or barley. Although resistance has been observed among var-

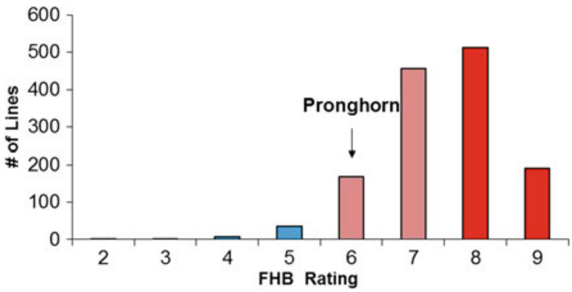

Fig. 2.2 Phenotypic evaluation of triticale germplasm lines for *Fusarium* head blight

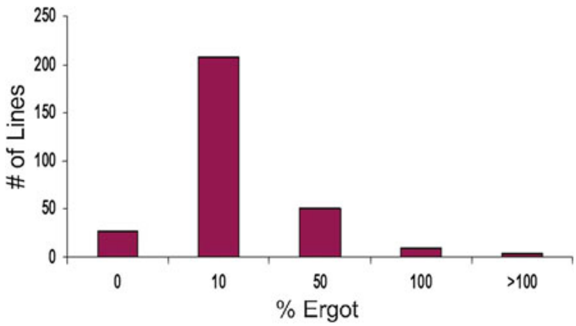

Fig. 2.3 Field reaction of spring triticale germplasm lines to ergot

ious germplasm lines (Lelley 2006) and resistance cultivars have been developed, limited information is available on genetics of leaf spot diseases in triticale.

Triticale is considered to be more tolerant to some abiotic stresses than wheat. The main limiting factors for grain production include environment stresses (drought, cold) and soil conditions (soil acidity, salinity, nutrient availability, and toxicities to aluminum and other elements (Lelley 2006)). Triticale is more vigorous, more adaptable and has greater yield with comparable inputs than either of its progenitor species. Modern triticale cultivars have consistently shown advantages and have outperformed existing cultivated cereal crops under marginal land conditions (Mergoum et al. 2009). For example, in Poland where over 60 % of arable soils are acidic, triticale has a competitive advantage in yield and biomass production over other cereals (Lelley 2006). Genetic variation for abiotic stresses exists in both triticale and rye; however, further improvements have been slow due to complex genetic and environment interactions.

(c) **Quality traits**

Although both ancestral species of triticale (sp. *Triticum*, sp. *Secale)* are used for human food, the utilization of triticale as human food is still sporadic. When selecting for quality traits, breeders must consider the needs of the end user and devise effective selection strategies for the traits of importance. At present, 90–95 % of triticale grain is used as livestock feed (mostly swine and poultry but also cattle, beef, and sheep) while ruminants can also use the forage for grazing, silage, green feed, and hay. Triticale has also started to be used as an energy crop for ethanol production. Further improvement in triticale end-use quality requires effective selection strategies which rely on quick, simple, inexpensive, and accurate analytical methods. Although significant improvements have been made in physical grain characteristics, many quality parameters still require major attention, particularly for human consumption. Kernel hardiness, protein quality, gluten strength, and bread-making quality are the main concerns in this regard. One of the major bottlenecks for the improvement of these traits is a lack of variability and poor understanding of the genetics of these traits in this species. Some of the progress made to date is discussed below.

Grain Physical Characteristics

The improvement of volume (or test) weight has been an extremely important objective for many triticale breeding programs because of its direct relationship with flour yield and grain energy content for feed. Despite improvements in volume weight and kernels with less shriveling, the volume weight of triticale remains lower than wheat. In Argentina, Aguirre et al. (2002) showed a range in volume weight of 60–72 kg/hL, with an average of 66 kg/hL. Volume weight had a weak negative correlation with protein content and a strong positive correlation with flour yield. In the USA, a multi-location study using 22 diverse genotypes had a range in volume weight from 68.3 to 75.0 kg/hL. The estimated average heritability (h) for volume weight ranged from 0.63 to 1.05 with a mean of 0.93 (Barnett et al. 2006). In Hungary, the mean test weight in a similar study was much the same (69.0 kg/hL) but the variation (64.0–77.0 kg/hL) was greater (Bona unpublished). Schori et al. (2007) examined the breeding progress achieved in Switzerland for volume weight based on breeding line data from 1988 to 2006 and reported that volume weight had been improved by 7 kg/hL. This evidence shows that genetic variation for volume weight appears to be fairly abundant and selection can be effective, although the inherent instability among the triticale genomes continues to contribute to generally slow progress.

Flour yield (or milling yield) is a complex trait. Volume weight is a good indicator of milling yield in triticale and has facilitated effective progress for this trait. As increase in volume weight and flour yield has been made, associations with other important quality characteristics have been reported. For example, while the relationship between volume weight and flour yield is positive, the relationship with grain protein concentration is negative, likely a result of increased starch content (Sullivan et al. 2007). Dennett and Trethowan (2013) found that triticale milling yield had a strong negative correlation with ash content ($r = -0.93$) and grain hardness ($r = -0.67$).

Kernel hardness is an important trait in the food and feed industry because it impacts postharvest handling and processing quality. Hexaploid triticale was originally characterized as a soft grain cereal. Generally, the soft texture of this crop has limited its utilization to cookies and biscuits. While the rye progenitor species is considered very soft, durum wheat has a very hard texture, resulting in a wide range of kernel hardness in current hexaploid germplasm. Effective tools for kernel hardness screening are available and useful in selecting the appropriate level of hardness. In a CIMMYT study of 171 hexaploid triticale lines, the average Single Kernel Characterization System (Perten—SKCS) hardness ranged from 8.6 to 83.9 (Li et al. 2006). In a recent study in Hungary, 144 hexaploid triticales ranged in SKCS kernel hardness from 25 to 88 with most genotypes in an intermediate hardness range. The study also showed that SKCS hardness was strongly affected by environment (Bona et al. unpublished). It has also been shown that selection against the R-genome secaloindoline hardness genes and other allelic variations can induce harder endosperm (Li et al. 2006; McGoverin et al. 2011).

Thousand kernel weight (TKW) or seed size is not only important as a primary yield component but also because it is associated with the overall end-use and nutritional quality of the grain. According to Gowda et al. (2011), TKW of triticale had high heritability (H = 0.85) based on a large collection of eastern European elite lines with significant variation (3.2–48 g/1000 seeds). In another recent study, the TKW of 144 advanced lines showed variation from 27 to 62 g/1000 seeds (Bona unpublished). Ukalska and Kociuba (2013) reported that selection for improved TKW in triticale will significantly improve grain yield. It is assumed that heavier kernel weights improve starch content but are likely to decrease the grain protein concentration. High grain yield, higher TKW with higher starch content, and low protein are desirable for the ethanol fermentation process.

Protein concentration and quality are important characteristics whereby improvements are equally desirable for animal feed and forage as well as for human consumption. The crude protein content of triticale grain varies from 9 to 20 % and the biological value of the protein is higher than wheat protein. Early triticale cultivars with poorly formed kernels had higher protein concentrations (14–20 %) than more recent cultivars with plump, high starch kernels (Oettler 2005). Today, most modern hexaploid winter triticales have a protein levels between 9 and 14 %, while spring types are 10–25 % higher. As is the case with other cereals, protein concentration is significantly affected by genotype, location and year (Bona et al. 2002; Alaru et al. 2003; Rakha et al. 2011; Lango et al. 2015). Over the past three decades, near-infrared (NIR) spectroscopy has offered rapid and reliable measurements of protein concentration, kernel hardness, ash content, and sedimentation volume (Manley et al. 2013) and has been adopted as standard tools in many breeding programs around the world. In the Schori et al. (2007) study examining breeding lines data from 1988 to 2006, grain protein concentration was improved by 0.2 %. Protein yield increased by 0.14 t/ha, thus progressing by 1.1–1.3 % per year. Despite improvements in crude protein content, the bread-making attributes of triticale remain undesirable due to poor protein quality. The gluten strength of triticale lines is generally low compared to wheat due to the presence of the rye genome as well as the absence of the wheat D genome contributed from *Triticum tauschii*, which contains many known bread quality genes. While the improvement of protein quality was an original objective for triticale breeding, several new developments may provide a promising path forward. New primary triticale populations produced by intercrossing *T. durum* germplasm carrying the favorable HMW glutenin alleles *Glu-A1b* (subunit2*) and *Glu-B1f* (13 + 16) with inbred *S. cereale* sources have resulted in germplasm with higher grain protein concentration and significantly greater gluten strength (Dennett et al. 2013a). Several researchers have suggested that triticale baking quality traits could be improved by substituting rye chromosomes or smaller chromosomal segments with chromosomes (or segments) from the wheat genome. Promising results were achieved by Lukaszewski (2006) through a series of chromosome 1D translocations where the *Glu-D1d* allele replaced *Sec-3* and where a segment replaced *Sec-1*. Although the use of these translocation lines has led to improvements in bread-making quality, future variety development for bakery utilization will depend on assembling the appropriate pattern of glutenin storage proteins encoded on wheat chromosomes A and B, and on the incorporation of germplasm with low hydrolytic enzyme (mainly alpha–amylase) activity (Wos et al. 2008; Grabovets et al. 2013).

PHS causes loss in both yield and quality, as it is associated with many nutritional and processing characteristics, e.g., dough viscosity, rheological properties, and gluten strength. The development of PHS resistant triticale cultivars with higher FN and low amylase activity is therefore a top priority in most breeding programs. Reduction in Hagberg FN is a good indicator of starch degradation by various enzymes activated during the sprouting process. High alpha–amylase activity differentiates triticale from its ancestral species; in most cases, triticales have lower FN than wheat and rye. The presence of high alpha–amylase in samples not subjected to pre-harvest sprouting conditions suggests that triticale may suffer from late-maturity amylase (LMA), similar to that observed in some wheat lines. The existing genetic variability for FN and alpha–amylase activity appears to be sufficient for breeders to improve these crucial characteristics in triticale, but there appears to be less variability than what is available in wheat (Oettler 2005). Under rain-affected conditions at harvest, Dennett et al. (2013b) found FN variation between 62 and 145 s in Australia, while a somewhat wider range (62–203 s) was detected in a European study (Bona unpublished). Quick selection using modern FN instruments along with molecular tools and rapid commercial kits is widely available for this goal (Mares and Oettler 1991; De Laethauwer et al. 2009, 2012; Dennett et al. 2013b). Nevertheless, it must be noted that triticale FN cannot be directly compared to wheat FN because factors in addition to alpha–amylase (i.e., certain endogenous enzymes and water-protein relations) greatly influence the viscosity of the triticale solution. Some of the newer rye lines have shown significant improvement in the FNs that are comparable to wheat. These lines could be incorporated into new primary triticale while further selection efforts will be required to improve these characteristics.

Generally, triticale has a dietary fiber content (DF) higher than wheat but lower than rye. Although triticale grain is used primarily as an animal feedstock, it is not always the first choice among livestock producers due to its high soluble DF content, which results in anti-nutritional effects in monogastric animals such as poultry and swine. Arabinoxylan (AX) is the predominant pentosan or non-starch polysaccharide (NSP) factor in triticale, ranging from 5.9–7.5 %, while the proportion of beta-glucans is lower (0.5–1 %) (Rakha et al. 2011, 2013). The high levels of soluble AX may cause problems in monogastric livestock but can be solved by adding commercial enzymes to the feed rations (Boros 2002; Cyran et al. 2002). Nevertheless, for human consumption and for ruminants, high DF and AX contents have tremendous nutritional advantages and increasing both the non-soluble and soluble fiber components would be desirable. Both Rakha et al. (2011) and Lango et al. (2015) found considerable genotypic variation for DF in triticale (13.2–16 %). Fine tuning of the analytical methodology specific for triticale may be required.

In summary, triticale quality breeding strategies may concentrate on: (a) grain for human consumption (demands of large-scale milling industry and bakeries, pasta products, functional foods); (b) grain for animal feed (monogastrics and ruminants); (c) forage (grazing and silage, green-fed, and hay for ruminants); and (d) utilization as an energy crop (mostly bioethanol from grain or full biomass utilization). Triticale is a young species and has the genetic potential to meet all of these needs.

Integration of Novel Technologies for Future Prospective

Triticale has a competitive advantage over other small grain cereals in terms of grain and biomass yield, and resistance to various biotic and abiotic stresses. Triticale crop development should focus on enhancing this competitive edge, with further gains in grain and biomass yield, tolerance to various stresses (nutrient and water use efficiencies, and diseases like *Fusarium* head blight, leaf spots, and ergot), the pillars of a stable supply. Further increases in yield potential will require improvements in harvest index by increasing responsiveness to fertilizer, stronger straw, and better partitioning of photosynthates. The use of hybrid triticale could also be exploited if there is sufficient amount of commercial heterosis and a viable seed production system available. Improvement in end-use quality for human consumption still poses significant challenges and will require a better understanding of the interactions among the wheat and rye genomes. Straw and grain constituents specifically enriched for biorefinery end-uses could also make triticale a dedicated industrial crop. To achieve these goals, triticale development programs require integration of new tools and technologies into existing breeding programs. Efforts to broaden the triticale germplasm base should continue through germplasm sharing and the synthesis of new primary triticales from wheat and rye. Genomics selection, functional genomics, and genome editing along with cytological tools will play important role for the synthesis of new generation of primary triticale. Identification and development of rye parental material that could provide stable genome balance in a wheat background will also be critical to the future improvement of triticale. Among the various novel breeding tools to develop new cultivars, doubled haploid production and genomics-assisted breeding (GAB) are getting attention in triticale breeding programs in recent years. The use of these tools increases selection efficiency and decreases cultivar development time. Doubled haploid plants are produced in plant breeding programs throughout the world to achieve homozygosity rapidly, reducing breeding cycles by 4–5 years. Inherent instability of triticale genome and intergenomic barriers limiting gene expression between wheat and rye are still posing considerable challenges to breeders (Baier and Gustafson 1996). Doubled haploid lines provide excellent opportunities for understanding inheritance of many traits as well as genetic mapping and development of genomics tools. With the advent of new genomic sequencing technologies, breeders are now able to characterize the genetic constitution of their germplasm at the DNA level. There has been a large increase in genomics technology, with complete genome sequences of many crops. Gene-specific single nucleotide polymorphism (SNP) markers can be developed very efficiently that can be used through GAB for tracking various traits. A large number of transcriptome resources for wheat, rye, and triticale are now available and enable the identification of sequence variants for the development of SNPs for tracking individual genes. The identification of specific SNPs will enable the tracking of specific genes in population progenies to accelerate development of lines for specific end-uses in conventional crosses. Further breeding efficiencies can be enhanced with the use of doubled haploid production in conjunction with genomic selections. This will lead to better decision made for parental selections, predicting crosses, reduce the work flow with early discard of undesirable progenies or populations, increase selection efficiencies in early generations, and significant reduction in cultivar development with desired improvements. These tools are already being adopted in other cereal (wheat and barley) breeding programs but triticale breeding programs still have to embrace these tools for cultivar development. As a non-food crop, triticale offers an opportunity and freedom to operate using genetic engineering. The integration of enabling technologies (transgenic, functional genomics, and targeted genome editing) with conventional plant breeding approaches will be pivotal for making designer triticale a successful crop.

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