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Synthetic Wheat: An Indispensable Pre-breeding Source for High Yield and Resistance to Biotic and Abiotic Stresses in Wheat Improvement

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ABSTRACT

In addition to being the most widely cultivated crop, wheat is also the most ancient cultivated plant species. Today, as in the past, wheat continues to be a crop of strategic importance. Cultivated hexaploid bread wheat (2n=42) consists of three genome groups (AA, BB, and DD), with each genome group further comprising three diploid wild species. Over the past 70 years, the world population has been rapidly increasing, while the area of agricultural lands has remained more or less constant. To be able to feed this continually increasing human population, scientists have begun to investigate the biological origins/roots of wheat, with the aim of achieving higher yield and greater resistance to biotic and abiotic stresses. This was because, based on the studies they performed, they determined that “reconstructing” wheat from its origins was a more effective solution than working with limited and currently available genetic resources. Bread wheat reconstructed by using diploid wild forms is called “synthetic wheat”. Synthetic wheat receives certain characteristics from wild forms that render them superior to cultivated wheat. Diploid wild forms bearing the “D” genome (*Aegilopstauschii*) are known to be particularly very resistant to biotic and abiotic stresses. Nowadays, it has become imperative to use synthetic wheat in order to increase genetic variation in breeding programs. To break the “yield per unit area” barrier, to ensure world peace, and to prevent the starvation of children around the world, wheat breeders must place greater emphasis on the production of synthetic wheat.

Keywords: Synthetic wheat, aegilops, D genome, crossing.

Introduction

The origin of cultivated wheat is Southwestern Asia. Archeological findings indicate that the earliest locations of wheat cultivation were regions corresponding to present-day Turkey, Syria, Jordan, and Iraq (Kirtok, 1997). Cultivated wheat first appeared nearly 10,000 years ago through the first hybrids and mutations of Emmer wheat (*Triticum turgidum* ssp. *dicoccoides*) (Yadon *et al*., 2000). It is very probable that the first Emmer wheat was distributed in Southeastern Turkey, in the environs of Diyarbakır’s Karacadağ (Heun *et al*., 1997; Luo *et al*., 2007). Throughout history, wheat has been an important cultivated plant for human nutrition; for this reason, it is also the cultivated plant on which the most breeding studies have been performed.

In the year 1900, the world population was nearly 1.6 billion (Chen and Shi, 2013), while world wheat production was at an estimated 90 million tons. Wheat production later reached 147 million tons by 1950

(FAO, 1952), and 586 million tons by 2000 (FAO, 2014). Meanwhile, the world population continued to increase rapidly, as well, reaching 2.5 billion in 1950, and 6.5 billion in 2000 (Bongaarts, 2009). It is estimated that the world population will reach 9.1 billion by 2050 (Atabay *et al*., 2014); therefore, to maintain the ratio of "wheat produced per person" in the year 2000, the world wheat production must be raised to approximately 820 million tons by the year 2050. Considering the effects of climate change and population increase, the general picture for food production and demand in the future appears rather bleak (Figure 1). For this reason, ensuring adequate food supply to the world population of the future - as well as preventing future food wars - necessitates important and bold approaches for increases in food production. Dr. Norman Borlaug, who was awarded the Nobel Peace Prize in *1970,* said that "if you desire peace, cultivate justice, but at the same time cultivate the fields to produce more bread; otherwise there will be no peace" (David, 2013).

Today, increasing the amount of agricultural lands around the world no longer seems possible. Quite the contrary, increasing urbanization and industrialization, as well as many other factors associated with the modern world, are causing a decrease in arable lands (Young, 1999; Cassman *et al*., 2003). In the 1950s, researchers placed emphasis on high-yield varieties to meet the world food demand, laying the foundations for a "green revolution". They were thus able to achieve higher yields, owing mainly to genetic advances that enabled greater yield potential and resistance to biotic and abiotic stresses in wheat varieties (Blum, 1996; Kaya *et al*., 2002; Reynolds and Borlaug, 2006; Rana *et al*., 2013). However, as of today, researchers have already used almost all available genetic resources in the world in studies aiming to develop high yield varieties. Consequently, they have already reached an impassable "ceiling" in terms of the maximum yield potential that can be achieved with current genetic materials. For this reason, to reach higher yields beyond this level, researchers have begun looking for new genetic materials for higher yield potential and greater resistance to biotic and abiotic stresses. Higher yield per unit area will hence be achieved through the efforts and studies of wheat breeders (Bindraban, 1996).

As of today, studies that initially began with the green revolution to develop higher yield varieties have already reached the highest yield level possible with current genetic materials, and the new varieties developed based on these materials (Rana *et al*., 2013). In recent new varieties, the increase achieved in annual yield are in the environs of just 1% (Sayre, 1990). As such, it has become necessary to initiate a new green revolution (Rana *et al*., 2013). Although the maximum yield levels achieved with wheat have gradually steadied and become constant in recent times, higher yields are still possible. The Quran, the holy book of Islam, describes that a single wheat seed can yield 700 seeds (Arslan, 1995). This target seems far beyond what is possible with present-day wheat yield levels.

In recent years, breeders have begun conducting extensive studies for expanding the gradually narrowing genetic basis and materials for wheat (Shiva, 1992) by using wild wheat forms to produce synthetic wheat. Numerous researchers have reported higher resistance to biotic and abiotic stresses in wild form, as well as higher adaptability (Shah *et al*., 1987; Cox, *et al*., 1994; Mujeeb–Kazi and Hettel, 1995; Mujeeb-Kazi, *et al*., 2008; Thompson, and Zwart, 2008). Hexaploid synthetic wheat serves as a genetic bridge for polygenic transfers between wild forms and cultivated bread wheat (Mujeeb-KaziandHettel, 1995; Calderini and Ortiz-Monasterio, 2003a).

Today, synthetic wheat appears to be the strongest candidates to obtain breeding materials that will enable the development of wheat varieties with higher yields and resistance to biotic and abiotic stresses.

What is synthetic wheat?

Synthetic hexaploid wheat is an interspecific hybrid obtained through the hybridization of *Triticum turgidum* ssp. *Dicoccum turgidum* (Emmer) and *Aegilops* groups (Mujeeb-Kazi and Hettel, 1995; Feuillet *et al*., 2008; Trethowan and Van Ginkel, 2009). Hexaploid synthetic wheat serves as a genetic bridge for polygenic transfers between wild forms and cultivated bread wheat (Mujeeb-Kaziand Hettel, 1995; Calderini and Ortiz-Monasterio, 2003b). The female progenitor of cultivated bread wheat is Emmer wheat (Matsuoka and Nasuda, 2004). On the other hand, the male donor for the "D" genome in bread wheat is *Aegilops tauschii* (McFadden and Sears, 1946; Feuillet *et al*., 2008) (Figure 2). Nowadays, the most commonly used diploid (2n=14) for the production of synthetic hexaploid wheat is the *Aegilops tauschii* (synonyms *Aegilops squarrosa* or *Triticum tauschii*) species (William *et al*., 1993; Mujeeb-Kazi and Hettel, 1995). Other diploid groups carrying the "D" genome include the *Triticum cylindricum, Triticum ventricocum, Triticum crassum, Triticum juvenile* and *Triticum syriacum* species (Kimber and Feldman, 1987).During synthetic wheat production, laboratory tissue culture techniques and chromosome doubling are used to ensure the germination of haploid hybrid seeds (Figure2).

The first synthetic wheat production began with the use of the colchicine technique (Sears, 1939) for chromosome doubling (Sears, 1941; Kihara, 1944; Sears, 1944; McFadden and Sears, 1946; Sears, 1955). Researchers have recommended the use of hexaploid synthetic wheat in breeding programs owing to their resistance to biotic and abiotic stresses (Shah *et al.*, 1987; Cox *et al.*, 1994; Mujeeb-Kazi and Hettel, 1995; Trethowan and Mujeeb-Kazi, 2008) and their yield potential (Villareal *et al.*, 1994; Lage *et al.*, 2004; Mujeeb-Kazi *et al.*, 2008).

Despite studies on synthetic wheat production from the 1940s to the early 1980s, no varieties were presented for farmers' use during this period. The first synthetic wheat-based varieties were presented to farmers for agricultural production during the 1980s (Gill *et al.*, 1985). Today, the number of synthetic wheat varieties produced by researchers has exceeded 1000.

We must use synthetic wheat in breeding programs. Why?

The greatest advantages of using synthetic hexaploid wheat as pre-breeding material are as follows: synthetic hexaploid wheat was produced based on a knowledge of their diploid and tetraploid parents' high resistance to biotic and abiotic stresses. Synthetic hexaploid wheat largely preserves these same characteristics, since they receive them from their parents in chromosome sets. Another advantage of synthetic hexaploidis that it is not a genetically modified organism, since it is obtained through the hybridization of wild goat-grass and durum wheat by using traditional methods. This is because synthetic wheat production is performed using natural genomes, without involving any foreign gene transfers.

1. Grain Yield and Yield Components

Primary synthetic wheat tend to have low yields (Trethowan and Van Ginkel, 2009). When primary synthetics are used in breeding programs, the desired level of yield can be attained by performing several backcrossings with the parent wheat (Trethowan and Van Ginkel, 2009; Trethowan and Mujeeb-Kazi, 2008).

Cooper *et al.*, (2012) previously reported that using synthetic wheat in hybridization programs by taking into account their number of ears, as well as the number of seeds in each ear, is a more effective approach for developing the grain yield of winter wheat. Synthetic wheat generally preserves their seed weight in different years and different locations (Cooper *et al.*, 2012). Furthermore, certain researchers have also observed that the sperm of primary synthetics resulted in wider grains, as well as higher seed weight (Cooper *et al.*, 2012; Cooper, 2013). On the other hand, Lage *et al.*, (2006) reported a considerable genetic variation among synthetic wheat in terms of grain weight and size.

In studies where synthetic wheat x spring wheat F_1 hybrids were backcrossed with the recurrent parent, researchers reported higher yields for these hybrids than their spring donor parents (Villareal *et al.*, 1994; Lage *et al.*, 2004; Mujeeb-Kazi *et al.*, 2008).Other researchers have reported that the use of synthetic wheat was positively and significantly related with higher grain yield, improved harvest index, improved grain weight, and higher biomass. Mohammad *et al.*, (2010) observed that in 33 of their experimental lines, synthetic wheat varieties weighted more by nearly 1000 kernels than all control varieties.

At the end of their two year study,Mujeeb-Kazi and Van Ginkel (2004) reported that the two varieties they produced from synthetic wheat were associated with 20% to 35% higher yields than commercial varieties. Similarly, Van Ginkel and Ogbonnaya (2007) reported that synthetic wheat was associated with 18% to 30% higher yields under heavy rain conditions compared to commercial varieties. According to the findings of other researchers (Del Blanco *et al.*, 2001; Ogbonnaya *et al.*, 2007), lines produced from synthetic wheat exhibited higher yield levels than their recurrent parents.

2. Grain Quality

A number of researchers have reported that the "D" genome carried by *Triticum tauschii* will enable the improvement of grain quality in wheat (Yueming *et al.*, 2003). Similarly, William *et al.*, (1993) reported that the superior grain qualities observed in *Ae. tauschii* represented a rich source for increasing the genetic quality/superiority of hexaploid bread wheat. Pfluger *et al.*, (2001) described that *Ae. tauschii* showed greater variability compared to bread wheat in terms of gliadin, gluteninand endosperm proteincontent. Lage *et al.,* (2006), on the other hand, reported significant genetic variation between synthetic wheat varieties with respect to the protein content and quality of their grains. Calderini and Ortiz-Monasterio (2003) reported that synthetic wheat possessed higher concentrations of macro and micro elements compared to commercial varieties. In contrast, Trethowan and Van Ginkel (2009) reported that primary synthetic wheat is more likely to have lower grain quality.

3. Resistance to biotic and abiotic stresses

In recent years, the production of synthetic wheat has gained further pace following the successful results obtained in breeding programs using synthetic hexaploid wheat as pre-breeding materials in order to assess their resistance against biotic and abiotic stresses. Numerous researchers who are concerned about the worldwide effects of climate change have published reports describing the resistance and tolerance of synthetic wheat to various biotic and abiotic stresses (Shah *et al*., 1987; Cox *et al*., 1994; Mujeeb-Kazi and Hettel, 1995; Trethowan and Mujeeb-Kazi, 2008).

Synthetic hexaploid wheat is resistant or tolerant to numerous disease-causing biotic factors. Some of these biotic factors includeleaf rust (Kerber, 1987), tan spots (Siedler *et al*., 1994), stem rust (Marais *et al*., 1994), stripe rust (Ma *et al*., 1995; Assefa and Fehrmann, 2000), karnal bunt (Villareal *et al*., 1996),spot blotch (Mujeeb-Kazi *et al*., 1996; Mujeeb-Kazi and Delgado, 1998), leaf blotch (Arraiano *et al*., 2001), cereal cyst nematodes (Eastwood *et al*., 1991), root lesion nematodes (Thompson *et al*., 1999), powdery mildew (Kong *et al*., 1999), glume blotch (Loughman *et al*., 2001), leaf blight (Mujeeb-Kazi *et al*., 2001), and hessian fly (Tyler and Hatchett, 1983).

Numerous researchers have also reported resistance or tolerance to abiotic stresses, as well as wider adaptability, among the wild forms that constitute the origin of bread wheat (Shah *et al*., 1987; Cox *et al*., 1994; Mujeeb–Kazi and Hettel, 1995; Mujeeb–Kazi *et al*., 2008; Thompson, and Zwart, 2008). Based on an experiment performed on *T. tauschii* lines and drought-resistant hexaploid lines held under low-water conditions, Reddy*et al*. (1996) demonstrated that *T. tauschii* lines were more tolerant. Other researchers determined that synthetic wheat has significant tolerance against salinity (Pritchard *et al*., 2002), drought, waterlogging (Villareal *et al*., 2001), frost at flowering and heat (Van Ginkel and Ogbonnaya, 2007).

Conclusion

Climate change is gradually increasing the average world temperature, while also reducing water resources and causing agricultural lands to become drier. Parallel to these negative developments, the world population is rapidly rising while the area of agricultural/arable lands remain constant. Many scientists believe that the inability to produce enough food to feed the increasing world population will inevitably lead to food wars. In this context, it is imperative to increase yield per unit area by developing varieties that are more resistant to biotic and abiotic stresses.

Until recently, new wheat varieties were developed using available genetic materials that have been used and reused for many years. However, these materials have not allowed researchers to achieve the desirable levels of resistance against the biotic and abiotic stress factors that limit grain/seed yield. To achieve such desirable traits in new varieties, it has become necessary to look at the origins of wheat. Understanding this necessity, researchers have focused in recent years on rediscovering the origins/roots of wheat, and on rebuilding it from a genetic standpoint. A general evaluation of the results obtained by researchers around the world clearly indicate varieties with higher yield potential, as well as tolerance and resistance to biotic and abiotic stresses, can be achieved through the greater use of synthetic hexaploid wheat as pre-breeding materials. To meet world food demand by the year 2050, we mustincrease wheat production by nearly 29% compared to present levels. Synthetic wheat currently represents the best and closest genetic source for developing higher-yield varieties. For this reason, wheat breeders must place greater emphasis on the production of synthetic wheat in order to ensure world peace, and to prevent the starvation of children around the world.

Figure 1.World population and wheat production in the years 1900, 1950, and 2000, and the estimated world population and wheat production for the year 2050.

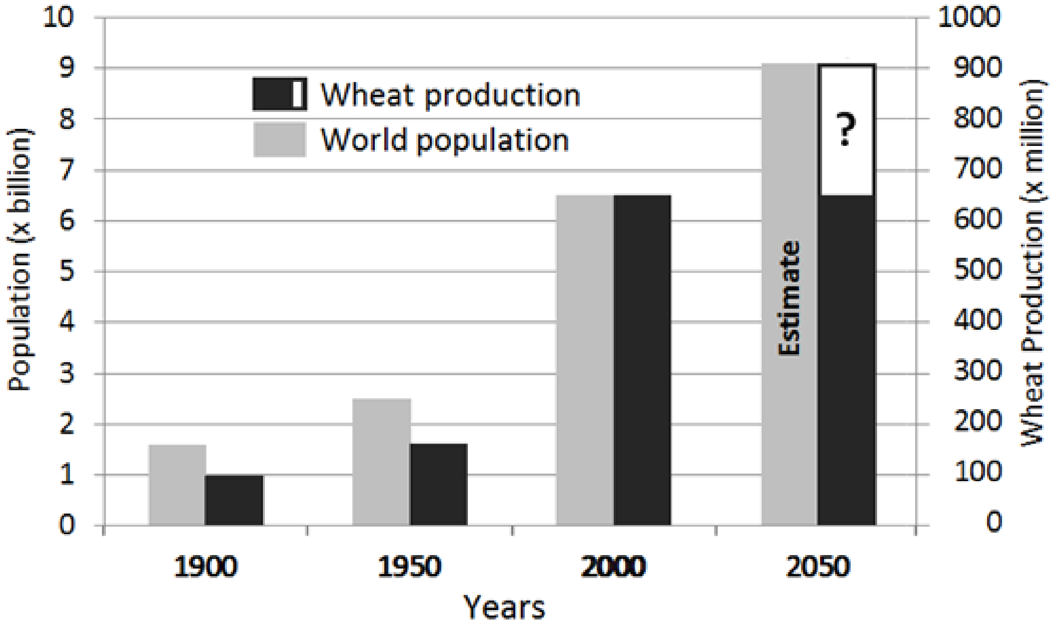
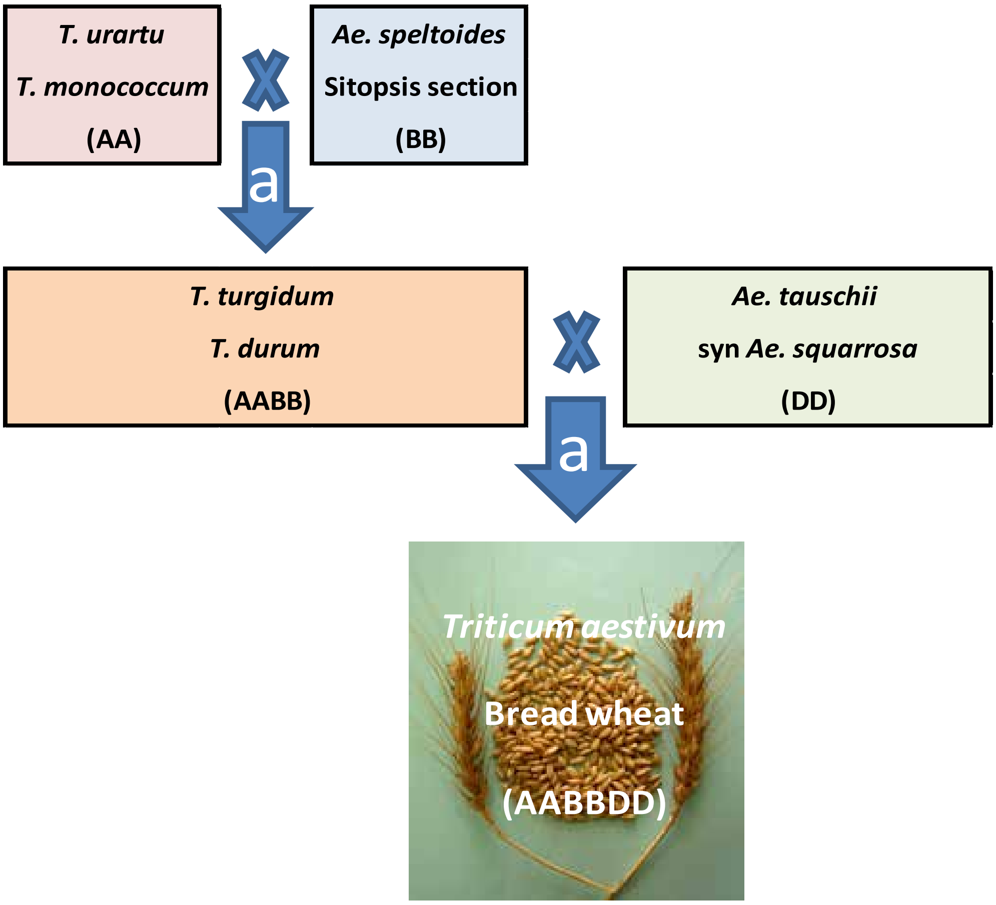


Figure 2. The origin of hexaploid bread wheat. Following each hybridization, fertility was ensured by performing chromosome doubling with the colchicine technique (a).



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