



Enhancing wheat production- A global perspective

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ABSTRACT

The world would require around 840 million tonnes of wheat by 2050 from current production level of 642 million tonnes and it has to be achieved with less land and resources through genetic, physiological and agronomic interventions particularly resource conservation technologies. Besides, precision breeding for improving varietal elasticity, new initiatives for climate change monitoring and crop modelling for advance yield forecasts would help in fulfilling future demands. The future strategies to mitigate adverse effects of climatic change, threat of new and emerging diseases, pests and weed flora, including the issue of increased herbicide resistance, deteriorating soil health need to be implemented to enhance genetic yield potential and sustainability. The researchers also need to explore options to increase yield components through photosynthetic capacity and efficiency, introduction of C₄ like traits—carbon concentrating mechanism, improving light interception, optimizing spike and canopy photosynthesis in future genotypes. The fast unravelling sequence information under various national and international projects might offer newer opportunities for reinventing wheat as a crop for ensuring food and nutritional security across the globe.

Key words: Conservation agriculture, Climate change, Genomics, Nutritional security, Productivity, Wheat

Wheat is one of the prehistoric crops which provides major energy requirement of the human diet across the world. Recent past has witnessed increased demand of wheat due to availability of wide range of end products at lower prices over other cereal crops. According to FAO estimate, world would require around 840 million tonnes of wheat by 2050 from its current production level of 642 million tonnes. This demand excludes the requirement of animal feed and adverse impacts of climate change on wheat production. To meet this demand, developing countries should increase their wheat production by 77% and more than 80% of demand should come from vertical expansion (FAO 2009). The production target is not very high, however, it has to be achieved when productivity growth in wheat is either stagnating or has slowed down across the globe. Besides, there is an urgent need for enhancing productivity through agronomic (water, nutrients, weed management etc.), genetic and physiological interventions along with resource conservation technologies. Basic and strategic research on climate change monitoring, adaptation, and crop modelling for advance yield forecasts would help in fulfilling future demands.

POPULATION VS. GLOBAL TRADE—A RETROSPECT

The survey report of FAO also estimates that North

African wheat imports would soar from 22.3 million tonnes in 2010 to 51.4 million tonnes in 2050 despite a negative wheat consumption per capita growth rate (Weigand 2011). The Middle East's imports will double from the region's minor wheat producers, from 14.4 million tonnes to 29.5 million tonnes. With both the highest population growth rate and wheat consumption per capita growth rate, Sub-Saharan Africa's wheat imports are expected to increase by 23.1 million tonnes by 2050. Indonesia's 2050 wheat imports will soar by 30 percent from 2010 imports, i.e. to 7.1 million tonnes (Weigand 2011). The Philippines' domestic demand for wheat will grow by over 60%, leading to imports of 4.5 million tonnes in 2050 (Weigand 2011). Brazilian wheat imports will climb from 6.5 million tonnes in 2010 to 10.5 million tonnes in 2050 in order to fulfil domestic demand. Mexico's wheat production will grow only slightly, but a negative population growth rate will keep wheat imports relatively steady through 2050. Similarly, wheat production in India has to match the population growth and thus country would require about 140 million tonnes of wheat by the year 2050 (Fig 1).

The world's significant wheat exporters are the US, Canada, Australia, The Black Sea Region, Europe, and Argentina. These countries are expected to see minimal, or even negative, population growth towards 2050. In contrast, population growth will be strongest in the countries of the tropic and subtropical regions where little wheat is grown. It is believed that, even without projecting large imports by China, the world wheat trade will likely double by 2050, to 240 million tonnes or more (Weigand 2011).

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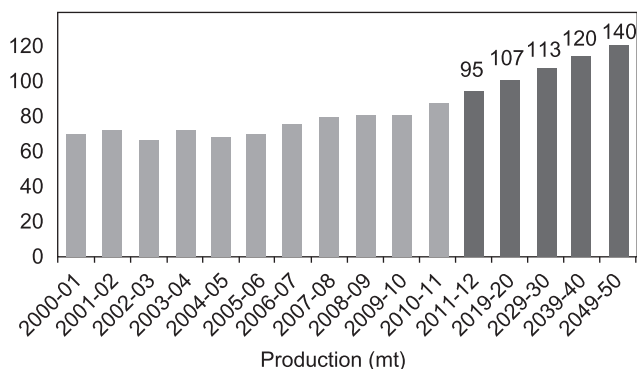


Fig 1 Wheat production in India-achieved and demands

Thus, realising that wheat already accounts for one third of all global grain trade by tonnage (Fig 2). Such a large expansion of trade will have major implications for all segments of the industry, including buyers, shippers, handlers and especially the producers in those countries that will supply the increased exports, including the United States.

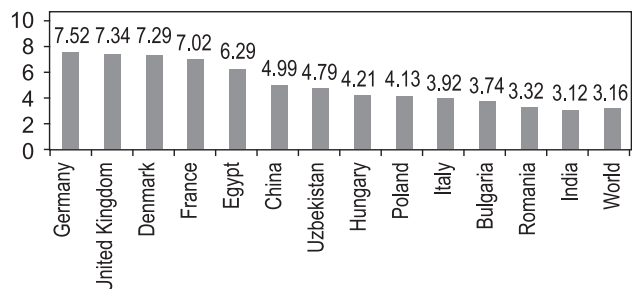


Fig 2 Comparative wheat yield (tonnes/ha) - India vis-à-vis other countries during 2013

Providing an adequate supply of food however, seems to be achieved at present for the current global population, sustaining this to future will be very challenging in view of steadily increasing population, increased purchasing power and continuously diminishing the availability of fertile cultivable land and water for agriculture. Meeting the expected demand is made even more difficult by projected changes to climate, particularly higher temperatures and changes to rainfall distribution and amount (Parry and Hawkesford 2010b, Lobell *et al.* 2011). Food supply will need to grow by 2–3% each year to meet the projected demand; but in the last decade the yields of the major cereals, rice, maize, and wheat have increased at less than half this rate (Ray *et al.* 2013) (Fig 3).

The FAO's report on world agriculture: Towards 2030/2050, further population increases will come in several countries with inadequate food consumption levels, pressuring for further increases of food supplies. Based on the population projections and wheat production and consumption growth rates used, the study found that wheat imports will be more than double for the countries like North Africa, the Middle East, Sub-Saharan Africa, Indonesia, the Philippines, Brazil, Mexico and other regions by 2050 (Table 1).

IMPACT OF CLIMATE CHANGE ON AGRICULTURE

According to researchers, climate change would force changes in diets around the world as some of the crops would be difficult to produce in the altered environment which can be subsidized by switching to crops which can thrive in those altered climates (IPCC 2001). Important

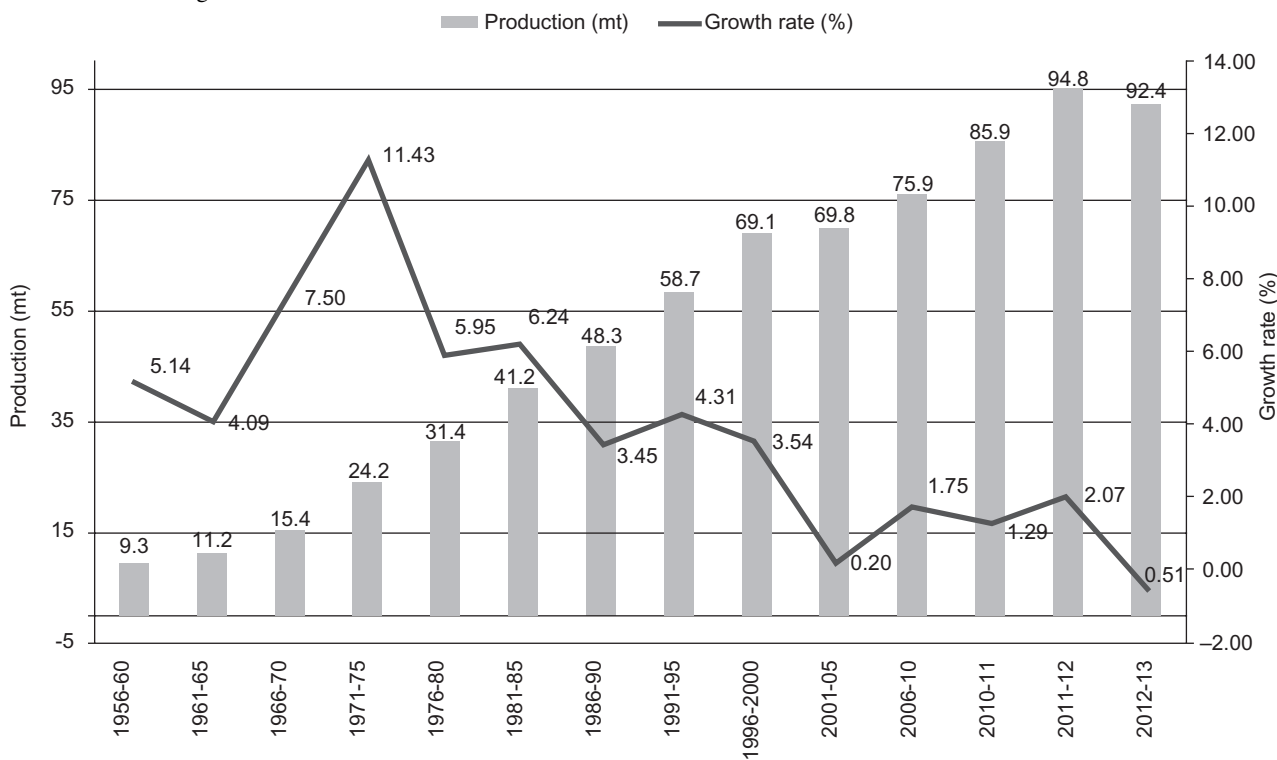


Fig 3 Trends for decadal growth rate and production of wheat in India during 1956-2013

Table 1 Population pressure for important countries

| Countries | Population (Millions) | | |
|--------------|-----------------------|------|------|
| | 1980 | 2010 | 2050 |
| Brazil | 122 | 195 | 219 |
| China | 986 | 1362 | 1426 |
| India | 693 | 1214 | 1614 |
| Indonesia | 147 | 233 | 288 |
| Mexico | 69 | 111 | 129 |
| Middle East | 53 | 133 | 243 |
| North Africa | 92 | 170 | 245 |
| Philippines | 48 | 94 | 146 |
| Sub-Saharan | 333 | 757 | 1598 |

Source: FAO's Report in World Agriculture: Towards 2030 / 2050.

crops like maize and wheat are more prone to be affected as they produce less grain at temperatures above 30 degrees Celsius. The impacts of climate change on food systems are expected to be widespread, complex, geographically and temporally variable, and profoundly influenced by socio-economic conditions (Vermeulen *et al.* 2012). Efforts to increase food production are nevertheless increasingly important as 60 percent more food will be needed by 2050 given current food consumption trends and assuming no significant reduction in food waste (FAO 2012, Singh *et al.* 2010).

The Asia-Pacific region is likely to face the worst impacts on cereal crop yields. Loss in yields of wheat, rice and maize are estimated in the vicinity of 50, 17 and 6 percent respectively by 2050 (IFPRI 2011). This yield loss will threaten the food security of at least 1.6 billion people in South Asia. The projected rise in temperature of 0.5°C to 1.2°C will be the major cause of grain yield reduction in most areas of South Asia (Anonymous 2013). In India, physical impact of climate change would cause an increase in the average surface temperature by 2-4°C, changes in rainfall (both distribution and frequency) during both *kharif* and *rabi* months, a decrease in the number of rainy days by more than 15 days, an increase in the intensity of rain by 1-4 mm/day and an increase in the frequency and intensity of cyclonic storms. With the changing food habits and market conditions, farmers prefer wheat or rice in most parts of the country. In most agro-climatic regions, farmers have stopped cultivation of millets which are suitable to a particular agro-climatic region. Climate change is projected to have serious implications for these major crops especially wheat (Anonymous 2013). India is considered to be the second largest producer of wheat (Anonymous 2014, Sharma *et al.* 2011 and 2013, Singh *et al.* 2012).

The Northern Indian states such as Uttar Pradesh, Punjab, Haryana, Uttarakhand and Himachal Pradesh are some of the major wheat producing states where the crop is more vulnerable at a 1°C rise in temperature resulting in reduction wheat yield (Singh *et al.* 2011). In Haryana, night temperatures during February and March in 2003-04 were recorded 3°C above normal, and subsequently wheat

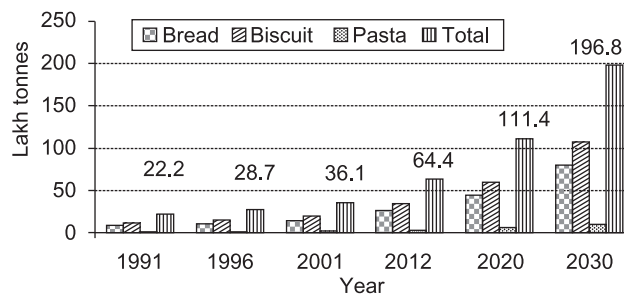


Fig 4 Wheat based products in India-present scenario and future projections

production declined from 4 106 kg/ha to 3 937 kg/ha during this period (Cooshalle Samuel 2007).

Even though the Indian wheat is traditionally known for *chapati*, promising varieties suitable for various other products like bread, biscuit, semolina, pasta, macaroni etc. have also been identified (Ram *et al.* 2011). India is rated as the second largest biscuit industry in the world. The demand for bread, biscuit and pasta is expected to increase @5.0 percent annually (Fig 4). Therefore, there is a big scope for focussing on wheat grain value addition. *Triticum dicoccum* has already established itself as a good cereal crop for sugar patients. Change in bran proportion in flour makes it more suitable for patients with chronic constipation.

CHALLENGES AND RESEARCH PRIORITIES

In view of the future challenges arising due to global climatic changes, new threats of diseases and pests, new weed flora, herbicide resistance, soil health and stagnated productivity levels, appropriate research strategies need to be developed to further enhance the yield potential and genetic diversity. The genetic variability is the very basis of any crop improvement program. The wild relatives, landraces and genetic stocks are the important sources for new genetic variations. However, it has been viewed that till date, the full potential of genetic resources has not been exploited in crop improvement programs and productivity gains through their use is continuously stagnant and the current efforts on research in the field of wheat hybrids are limited with not much success. Under the changing climate, it is essential to breed short duration varieties with high per day productivity rather than developing long duration high yielding varieties of wheat.

The new varieties of wheat should possess genes/QTLs responsible for providing resistance/tolerance not only to major diseases and insect-pests, but also to have tolerance to terminal heat, drought, salinity-alkalinity and cold. The nature's gift in the form of vast fertile tract of Indo-Gangetic plains alone offers ample opportunity for enhancing food production to a much higher level.

However, wheat breeding in combination with agronomic manipulation for exploiting the positive interactions between genotype and cropping systems management also has great potential. A multipronged strategy involving germplasm development for biotic, abiotic and quality traits supported by Marker Assisted Selection

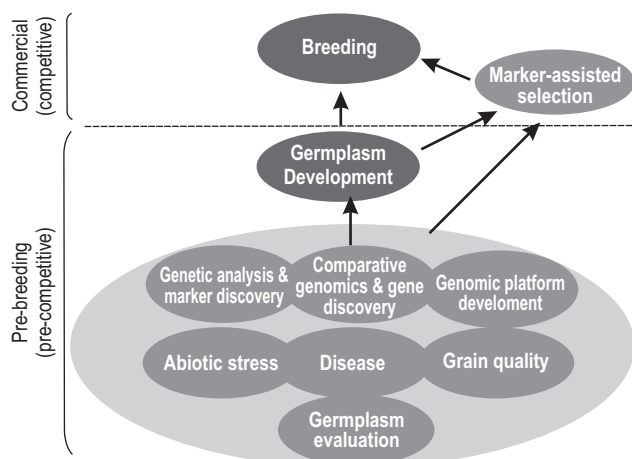


Fig 5 Wheat improvement strategy for managing important aspects

(MAS) is the need at this moment to improve the yield levels and mitigate the climate change effects (Fig 5).

Heterosis and hybrid: Wheat is one of the most systematically evolved crops wherein there is extensive introgression of one gene pool into another gene pool in different wheat based agro-climatic zones. Heterosis, a major successful technology which has effected major productivity gains in other cereals, is to be adopted in wheat for increasing the yield potential of the wheat for breaking yield barriers. The availability of CMS sources and fertility restorers has increased the possibility for hybrid wheat development. The issues in identification of heterosis can be addressed through components like matching the yield components to achieve yield maximization in hybrids, diversity in parental lines, hybrid x environment interaction, use of other characters like disease resistance, quality as a pre-requisite to develop superior hybrids, exploring the advantage of allopolyploidy in wheat.

Broadening of genetic base of varieties (pre-breeding): The genomes of modern wheat varieties have originated 10000 years ago from land races. Over the years, quantitative gains have been incorporated through the deployment of already selected alleles into new combinations (Feldman *et al.* 1995). This is a very efficient approach for the fine tuning of germplasm for specific environments.

However, the search for new and useful allelic variation outside of adapted germplasm is challenging for commercial wheat breeders. Sharing of germplasm from many countries, e.g. USA, Canada, Australia, China, Syria and South Africa could be one option to breed for different set of conditions. Systematic efforts on building up germplasm collections and identification of potential donors for various traits would open up new opportunities for wheat scientists. The major problem in using distantly related wheat lines is the much longer duration of breeding process before commercially relevant materials can be created. Following points are important for consideration during pre-breeding.

- Multiplication, curation and phenotyping of germplasm.
- Mining novel alleles for genes of known function.
- Production of segregating populations for lines of

interest identified in primary germplasm screens.

- Use existing landrace x elite segregating populations to identify environmental niche specific QTLs controlling traits of interest.
- Production of NILs for QTLs and allelic variants.
- Assessing agronomic performance of NILs.
- Development of informative genetic markers and their use in commercial wheat breeding programmes.

Development of new plant types: Engineering the plant genetic architecture is a new emerging area to enhance wheat production across the world. Physiological parameters like increased radiation use efficiency, rate of grain filling, number of grains/spike, nutrient uptake, stem reserve mobilization are some of the focused issues for creating new plant type. In green revolution varieties plant height reduced to avoid lodging, especially under high yield potential conditions, and allowing higher inputs to be applied to the crop (e.g. fertilizers) to increase yield (Fischer and Stockman 1986). However, the most revolutionary impact of the green revolution was a clear and consistent improvement in the internal partitioning of the plants promoting increases in spike weight due to a reduced competition for carbohydrates between spike and stem. In fact, the spike to stem ratio was increased sharply in new cultivars released after the green revolution compared with older cultivars (Calderini *et al.* 1997). Plant height reduction increased the harvest index (HI, i.e. the biomass partitioning to the reproductive organs, the grains). The key to increase production is the establishment of a photosynthetically active canopy, optimized for the production of photoassimilate that determines the final grain yield (Nagarajan 1998). Approaches to increasing carbon fixation are optimizing canopy architecture and light capture efficiency (targeting complete canopy closure or maximizing leaf angle for light interception), modification of intrinsic photosynthetic efficiency and extension of the grain filling period. Thus architecture needs to be optimized not only for maximum light capture but also traits to avoid disease spread and lodging. A secondary but important role of the canopy is N-assimilation and N-storage (as protein), and the subsequent effective remobilization of this N to the grain during crop maturation.

Pre-harvest sprouting (PHS)

Germination of wheat within the spike before harvest is called pre-harvest sprouting (PHS). Periods of prolonged rainfall and high humidity after the grain has ripened and before it can be harvested can contribute to PHS. PHS can be visualized by kernel swelling, germ discoloration, seed-coat splitting, and the root and shoot emerging (Groos *et al.* 2002). PHS leads to reduced yield and grain quality which limits end-use applications for wheat result in substantial financial losses to farmers and food processors. The tolerance of PHS could be induced by environmental conditions, genotypes, quantitative trait loci (QTLs) and the interaction between these factors (Flintham 2000, Mares *et al.* 2005). Breeding for PHS-tolerant cultivars are highly

desirable in wheat growing areas where long periods of wet weather occur frequently during harvest. Studying the detailed effect of numerous factors of PHS is essential to improve the PHS-tolerance in wheat. In addition, selecting and mining new germplasm could help breeding PHS-tolerant varieties. For example, RSP (*Triticum turgidum-Aegilops tauschii*) with extreme PHS tolerance is the artificial synthetic hexaploid wheat crossed between *Aegilops tauschii* Cosson and tetraploid wheat (*T. turgidum* L.) (Lan *et al.* 2005). Future breeding programme should be diverted to integrate with PHS tolerance, better quality and high yield.

Manipulating photosynthesis efficiency (C₃ to C₄): The primary determinant in crop biomass is the photosynthesis of the growing season while other constraints do not become limiting. Increasing photosynthesis by enhancing the substrate CO₂ has been clearly demonstrated to increase yields (Ainsworth and Long 2005). This cumulative photosynthesis can be increased by increasing photosynthetic rate, light interception, or its duration. In some regions, it may be possible to increase the duration of photosynthesis but the growing season is most often constrained either by environmental factors (low/high temperatures and water availability) or by the cropping system. However, there are still opportunities to increase photosynthesis by improving early vigour and by manipulating senescence to delay its onset. Despite the fact that there is considerable variation in the structure of modern wheat canopies (e.g. flag leaf size and leaf angle) light interception is very important for further improvements in photosynthesis (Murchie *et al.* 2009, Reynolds *et al.* 2012). The biggest potential gains in cumulated photosynthesis would be achieved by increasing the photosynthetic rate. In wheat, only 4.6% of the intercepted radiation is converted to photosynthate, therefore, there is a good scope for improvement (Zhu *et al.* 2010). Numerous potential ways to increase photosynthetic rate have been identified (Parry *et al.* 2011). Many of these focus on increasing the concentration of CO₂ within the leaf. Simply increasing stomatal and mesophyll conductance will increase photosynthetic rate and yield (Fischer *et al.* 1998) but may decrease water use efficiency.

An alternative and perhaps simpler approach is to replace the CO₂-fixing enzyme, Rubisco, with one that would deliver higher photosynthetic rates (Hawkesford 2013). There is variation in the kinetic properties of Rubisco isolated from different species (Parry *et al.* 1989, Delgado *et al.* 1995, Galmes *et al.* 2005) that is sufficient to at least in theory confer superior characteristics to photosynthesis in wheat (Zhu *et al.* 2010, Parry *et al.* 2011). However, it is not currently possible to do this in wheat (Parry *et al.* 2013). In summary we can increase photosynthetic capacity and efficiency through improving performance and regulation of Rubisco, introduction of C₄ like trait-carbon concentrating mechanism, improving light interception, optimizing spike and canopy photosynthesis. Besides, now onwards due attention and research efforts need to be in

place for micronutrient efficient breeding strategies for stable yields (Jag Shoran *et al.* 2011). Synthetic wheat hexaploids have the potential to improve current levels of Zn efficiency in modern wheat genotypes. These efficient cultivars have lower external B or Zn requirements, and are able to extract the low levels of B or Zn efficiently. At the same time, they are also able to utilize the micronutrients more efficiently for growth. Much needs to be done to meet crop requirements for micronutrients that are relatively small, but their deficiencies greatly limit the effectiveness of macronutrients. Since micronutrient deficiencies are posing a problem in Indian population, all efforts have to be made to evolve efficient wheat varieties having rich contents of micronutrients like, beta carotene, copper, zinc, iron, manganese etc. To improve nutrient use efficiency, their requirement should be worked out for the entire cropping system. Similarly, bio-fertilizers should be amalgamated in cultivation to enhance the efficiency of inorganic fertilizers. The genetic variation in Fe, Zn and Mn efficiency will allow more efficient genotypes of wheat to be developed in future.

MITIGATION OF DROUGHT AND HEAT

Wheat crop has the adverse effect on yield and quality due to heat as well as drought. Thus recognising the importance of these two factors, the breeding program should be designed based on architecting genotypes with water and nutrient efficiency. Physiological traits associated with heat and drought have been identified as canopy temperature depression, membrane thermo stability, leaf chlorophyll content during grain filling, leaf conductance and photosynthesis (Reynolds *et al.* 1998). Approaches to incorporate stress inducible regulatory genes that encode proteins such as transcription factors (DREB1A) are also being pursued (Hoisington and Ortiz 2008) in various laboratories.

Biotechnology a boost for food production

Marker assisted breeding: Rapid amalgamation of molecular markers shows important technological advances which are extensively used to improve the breeding efficiency in wheat. In addition, it has several other potentials new opportunities such as breeding for rust resistance, marker assisted background selection (MABs) for rapid adaptation of mega varieties, marker assisted selection (MAS) breeding for resistance, genome wide selection approaches for handling complex traits including yield and tolerance to abiotic stresses and molecular marker based monitoring of evolutionary and short term pathogen dynamics for devising effective control strategies.

Use of genomics: The fast unravelling sequence information under various national and international projects offers unprecedented opportunities for reinventing wheat and taking it to a new status as a crop. Some of the more immediate opportunities may be listed as:

- Allele mining on the basis of probing germplasm sets for specific gene sequences

- Innumerable new molecular markers in genomic regions of choice to facilitate large scale cloning of new genes
- A plethora of approaches for understanding the function of each and every gene
- Understanding temporal and tissue specific gene expression in response to developmental and environmental cues.
- Uncovering molecular basis of complex adaptation syndromes including tolerance to various abiotic stresses.
- Designing of a genome wide perfect marker system based on SNPs in entire gene space of the species.

Recently, deciphered wheat genome sequence is available in the public domain. Due to the presence of three sets of homoeologous chromosomes in the genome, it was considered a tedious job to characterize ~17 GB (17000 million base pairs) of wheat genome for their function (Brenchley *et al.* 2012, Ling *et al.* 2013). International Wheat Genome Sequencing Consortium (IWGSC) has published a “chromosome based draft sequence of the bread wheat genome” in journal *Science* (18 July 2014). The full wheat genome is about six times the size of human genome. Top international recall, Arabidopsis and rice have been sequenced many years ago but still functional gene characterization is on progress. Unless the genes are known for their function, would not be suitable for molecular breeders to fasten their breeding programme. Therefore, with a chromosome based full sequence in hand, wheat breeders would have now high throughput tools to identify how genes control complex traits like yield, quality, diseases, tolerance to drought, heat and hostile soils which will help in accelerating breeding programs. It will provide a large number of makers for DNA finger printing, diversity analysis and marker assisted breeding in wheat.

Reverse genetics would again be a viable tool to give function to the wheat genes which again require very good running protocol of wheat transformation. Therefore, integrated approach of wheat transformation protocol for genomic characterization would help to devise the molecular breeding programme for increasing wheat production to feed ever growing world population.

GM wheat: Genetic engineering can be used to modify the genetic compositions of plants. The number of genes that have been isolated and are available for transfer is growing daily. Thousands of such products have been field tested and over a dozen have been approved for commercial use. The traits most commonly introduced into crops are herbicide tolerance, insect tolerance, and virus tolerance.

Presently no wheat transgenics have been released anywhere in the world and public opinion for its acceptance remains, at best, divided. As of 2013, 34 field trials of wheat transgenics have taken place in Europe and 419 have taken place in the US. Modifications tested include those to create resistance to herbicides, insects, fungal pathogens (especially *Fusarium*) and viruses, tolerance to drought, salinity and heat, increased content of glutenin, higher protein content, increased heat stability of phytase, increased

content of water-soluble dietary fiber, increased lysine content, improved qualities for use as biofuel feedstock, production of drugs via pharming, and yield increases.

Thus we see a broadening of the transgenic wheat agenda with some activity even in Europe, conventionally associated with strong anti-GM sentiment. Rothamsted Research, UK, has applied for release of transgenic wheat genetically modified to produce a hormonal chemical compound that acts as an alarm signal to move aphids from the crop or deter them from landing on it. This chemical, the pheromone sesquiterpene-beta-farnesene (EBF), is produced by aphids when they are being attacked by predators and parasites.

As this transgenic addresses an environmental concern, it is expected to encounter less resistance. Notwithstanding the recent furore over unexpected detection of ‘Round Up Ready’ wheat plants in an Oregon farm in US, there are indications of a revival of interest in wheat transgenics in public as well as private sector. The opportunity provided by wheat transgenics particularly in context of tolerance to heat, drought and other adverse environments where wheat gene pool may fall short of the required variation cannot be ignored, particularly by the public sector research.

Enhancing wheat yields through improved resistance: The host resistance is the cheapest, effective and environmental friendly means of controlling the menace of three rust diseases. In fact, there had not been any serious rust epidemic in India during last four decades due to deployment of rust resistance genes in form of improved wheat varieties released for commercial cultivation (Singh *et al.* 2011). So far, quite few resistant genes against rust diseases have been utilized by wheat breeders in our country (Table 2).

The yellow rust disease is prevalent in northern and southern hills, north western and north eastern plains of the country. However, the central and peninsular parts remain free from this disease due to unfavourable weather conditions. For keeping yellow rust under control, new *Yr* genes like *Yr5*, *Yr10*, *Yr15*, Cappelle Desprez and China 84-40022 are being utilized effectively in the breeding programme in India (Sharma *et al.* 2011 and 2013).

Several genes showing avirulence against rusts and powdery mildew have been identified across the globe and through molecular markers these are being introgressed into suitable agronomic backgrounds. During the previous decade a gene combination *Lr26/Sr31/Yr9* was very popular and effective, but now it is not giving the desired resistance

Table 2 List of widely used resistance genes for three rusts of wheat

| Rust | Number of genes | List of known effective genes |
|-------------|-----------------|---|
| Leaf rust | <i>Lr</i> (10) | <i>Lr1</i> , <i>Lr 3</i> , <i>Lr 10</i> , <i>Lr 13</i> , <i>Lr 18</i> , <i>Lr 23</i> , <i>Lr 24</i> , <i>Lr 26</i> , <i>Lr 28</i> , <i>Lr 34</i> |
| Stem rust | <i>Sr</i> (13) | <i>Sr2</i> , <i>Sr 5</i> , <i>Sr 7b</i> , <i>Sr 8a</i> , <i>Sr 8b</i> , <i>Sr 9b</i> , <i>Sr 9e</i> , <i>Sr 11</i> , <i>Sr 12</i> , <i>Sr 13</i> , <i>Sr 24</i> , <i>Sr 30</i> , <i>Sr 31</i> |
| Yellow rust | <i>Yr</i> (5) | <i>Yr2</i> , <i>YrA</i> , <i>Yr9</i> , <i>Yr18</i> , <i>Yr27</i> |

and hence the proportion genotypes under advance evaluation trials have dropped 40-25%. It is now suggested to introgress the new and effective combinations like *Lr34/Yr18/Sr57/Pm38/Ltn1*; *Lr46/Yr29/Sr58/Pm39/Ltn2*; *Sr2/Yr30*; *Lr67/Yr46/Sr55* (AL) etc. (Sharma *et al.* 2011 and 2013).

Many genes particularly not used in wheat improvement very extensively but that may have good chance of showing resistance are *Sr27* of rye origin, *Sr22* and *Sr35* from *monococcum* (Table 3). With the help of pre breeding program some important genes showing avirulence to most of the races must be explored and transferred into the widely adopted varieties (Sharma *et al.* 2013).

Among other diseases which need immediate attention in breeding for resistance are Karnal bunt, foliar blight, powdery mildew and loose smut. Although, the incidence of Karnal bunt disease is presently not as severe as it used to be during eighties and nineties, however, due to its cosmetic nature and ban for trading in international market, breeding efforts need to be continued for the development of resistant varieties. The resistance donors for Karnal bunt disease are now available in both bread wheat (HD 29, HD 30, W 485, W 1786, KBRL 10, KBRL 13, KBRL 22, ML 1194, WL 3093, WL 3203, WL 3526, WL 3534, HP 1531, ISD 227-5) and durum wheat (D 482, D 873, D 879, D 895) for breeding purpose. Resistance has been incorporated in high yielding wheat varieties like PBW 343 and WH 542 by back crossing. Chromosome region (4B, 6B and 5A) linked to KB resistance have been identified. Similarly, developing resistant cultivars against foliar blight with availability of resistance donors like BH 1146, YM#6, Chirya, Harit 1(M 3), LBRL 1, LBRL 4, LBRL 6, LBRL 11, LBRL 13, DBW 46 etc. have potential to improve yields under hot and humid climates (Sharma *et al.* 2013).

Table 3 Important rust resistant genes and their wild sources

| Important gene | Source |
|-----------------------|---|
| <i>Yellow rust</i> | |
| <i>Yr11</i> | Joss Cambier |
| <i>Yr14</i> | Kador |
| <i>Yr15</i> | <i>Triticum turgidum</i> var. <i>dicoccoides</i> G-25 |
| <i>Yr24</i> | <i>Triticum turgidum</i> |
| <i>Brown rust</i> | |
| <i>Lr24</i> | <i>Thinopyrum ponticum</i> |
| <i>Lr25</i> | <i>Secale cereale</i> |
| <i>Lr27</i> | <i>Triticum aestivum</i> |
| <i>Lr32,Lr39,Lr42</i> | <i>Triticum tauschii</i> |
| <i>Lr45</i> | <i>Secale cereale</i> |
| <i>Black rust</i> | |
| <i>Sr26</i> | <i>Aegilops elongatum</i> |
| <i>Sr27</i> | <i>Secale cereale</i> |
| <i>Sr32</i> | <i>Aegilops speltoides</i> |
| <i>Sr35</i> | <i>Triticum monococcum</i> |
| <i>Sr39</i> | <i>Aegilops speltoides</i> |
| <i>Sr40</i> | <i>Triticum timopheevii</i> ssp. <i>armeniacum</i> |

High level of resistance could be achieved by pyramiding cassette of genes and using the molecular approaches. Fortunately, there is no serious problem of any insect-pest in our country in wheat crop. The incidences of termites and aphids have sometimes been reported from certain parts, which can be controlled by use of recommended insecticides. In the same way, loose smut and powdery mildew diseases of wheat are very well managed through seed treatment and spray of recommended fungicides, respectively. Nevertheless, in view of decreasing water table and increasing temperature, both termites and aphids may become prominent threats to wheat crop in future (Sharma *et al.* 2013).

Maximizing yields by agronomic interventions: For ensuring wheat production, adoption of conservation agriculture (CA) technology on a large scale is to be ensured through up-scaling of this innovation on large scale. Thus, without improved and efficient crop management, it will be difficult to harness the full potential of improved varieties and new production technologies. There is need to emphasize more on improved agronomic management/precision farming with ecosystem approaches, additional quantity of wheat is likely to be produced with limited resources and use of conservation agriculture technologies. Once perfected, these resource conservation technologies will have great impact being environment friendly, more productive and profitable as well as sustainable. Thus, use of improved varieties as well as efficient crop management practices would reduce input costs, increase yields and ensure higher net profits to smallholder wheat producers (Singh *et al.* 2011).

To enhance wheat productivity at farmers' field, specific technologies have to be developed for establishing a proper crop stand, irrigation management, fertilizer management, weed management, new resources conservation technologies and farm mechanization. The selection of a suitable variety by the farmer is the first and primary aspect of package to enhance yields through matching technology. Seed rate requirement is dependent on seed size, germination percentage, time and method of sowing. In case of FIRBS seed rate can be reduced to 75 kg per hectare. For late sown wheat and bold seeded varieties, seed rate should be increased by 25 percent, i.e. 125 kg/ha (Sharma *et al.* 2013).

Seeding depth should be 5-6 cm with an inter-row distance of 17.5-22.5 cm for timely sown and 15-17.5 cm for late sown wheat. Sowing using seed drill is better than broadcasting. In total, wheat crop requires 40 cm water and it needs external water supply when available soil moisture percentage falls below 50-60 percent of the field capacity. The crop requires 4-6 irrigations depending upon rainfall and water use of the crop. Crown root initiation (CRI) and heading stages are the most critical to moisture stress. The water use efficiency decreased with increasing number of irrigations but increased with increase in surface retained residue load from 1 to 6 tonnes/ha (Sharma *et al.* 2011).

Weed management: Weed is one of the major biotic constraints in wheat production as they compete with crop

Table 4 Promising herbicides for control of different types of weeds in wheat

| Weed flora | Herbicides | Dose (a.i./ha) | Time of application |
|------------------------------------|----------------------------|---------------------------|--------------------------|
| | | Product dose (g or ml/ha) | DAS |
| Grasses | Clodinafop | 60 | Post emergence 30-35 DAS |
| | Fenoxaprop-ethyl | 100-120 | Post emergence 30-35 DAS |
| | Pinoxaden | 40-50 | Post emergence 30-35 DAS |
| | Sulfosulfuron | 25 | Post emergence 30-35 DAS |
| | Isoproturon | 1000 | Post emergence 30-35 DAS |
| | Pendimethalin | 1000-1500 | Pre-emergence 1-3 DAS |
| Broad-leaved weeds | 2,4-D-E | 500 | Post emergence 30-35 DAS |
| | Metsulfuron | 4 | Post emergence 30-35 DAS |
| | Carfentrazone | 20 | Post emergence 30-35 DAS |
| | Pendimethalin | 1000-1500 | Pre-emergence 1-3 DAS |
| Both grassy and broad-leaved weeds | Sulfosulfuron | 25 | Post emergence 30-35 DAS |
| | Pendimethalin | 1000-150 | Pre-emergence 1-3 DAS |
| | Isoproturon+2,4-D E | 750 + 500 | Post emergence 30-35 DAS |
| | Sulfosulfuron+ metsulfuron | 30 +2 | Post emergence 30-35 DAS |

plants for moisture, nutrients, light and space and wheat is infested with both grasses and broad-leaved weeds. Increased use of fertilizers and irrigation, there was increased infestation of grassy weeds. *Phalaris minor* is one of the grass weed favoured by these improved cultured wheat production technologies. In the areas having the problem of isoproturon resistance to *Phalaris minor*, it is suggested to use sulfosulfuron, or clodinafop or fenoxaprop or pendimethalin or pinoxaden. Sulfosulfuron, and pendimethalin are effective against both grassy and non-grassy weeds, whereas, clodinafop, fenoxaprop and pinoxaden are specific to grasses.

For the control of complex weed flora combination of herbicides should be applied. Sulfosulfuron + metsulfuron and isoproturon with 2, 4-D or metsulfuron can be used as tank mixture. Grass herbicides (clodinafop, fenoxaprop, and pinoxaden) should not be tank mixed with either 2, 4-D or metsulfuron and to avoid antagonism the grass and broad-leaved herbicides should be applied sequentially.

For the management of multiple herbicide resistance, we need to revive some of the old herbicides like *Pendimethalin*, *Trifluralin* and *Terbutryn*. For post emergence weed control, metribuzin may be used with care in combination with grass herbicides like Fenoxaprop, Clodinafop and Pinoxaden (Table 4).

Resource conservation technologies (RCTs): Yield advantage of >15 percent has been observed after laser levelling the field. In addition to higher yield, the water saving is 35-45 percent due to higher application efficiency, increased nutrient use efficiency by 15-25 percent and reduced weed problem.

Zero tillage is direct drilling in untilled condition, a simple, and affordable technology which advances sowing time, seeds at comparatively higher moisture, saves more than 70% fuel energy and time for sowing/establishment, yield advantage due to advanced sowing, low infestation of *Phalaris minor* due to reduced germination and water saving. Furrow Irrigated Raised Bed (FIRB) technology works as

catalyst for diversification of rice-wheat system. In this planting method, crop is grown on top of bed and irrigation is applied in furrows. There are many additional benefits including lesser seed and nutrient requirement, opportunity for enhancing diversification and intercropping.

Rice residue is an important issue and field baling has been suggested as an option for collecting the huge amount of straw left after combining in order to decrease the adverse effects of open field burning on environment. Recently straw combines were introduced to collect crop residues especially wheat to be used as animal fodder.

In addition, in order to slow down the impact of climate change, adopting resource conservation technologies like zero tillage and bed planting especially with surface residue retention using second-generation seeding machines like Rotary Disc Drill and Happy Seeder can help in avoiding burning which adds to environmental pollution. Moreover, it will help in temperature moderation and offsetting the adverse effect of rising temperature in addition to improving the health of soil.

In addition, improving soil health by increasing carbon content, correction of micro-nutrient deficiencies/toxicity and balanced use of fertilizers are some of the very relevant issues that limits wheat productivity over time. Time has



come to strengthen experimentation to explore organic farming, use of agriculturally important micro-organisms, bio-agents and promoting biological control of pests and diseases in the changing scenario (Sharma *et al.* 2013).

The major researchable areas needing greater thrust include breeding strategies for enhancing productivity, application of molecular breeding for biotic and abiotic stresses, resource optimization for enhanced productivity, tackling ill effects of climate change particularly new races of rusts and other emerging diseases, enhancing value addition and quality improvement and managing impact of climate change on sustainable production of wheat. The wheat scientists should pay greater attention to conservation agriculture, improving soil health, input use efficiency, mechanization and diversification of cropping system. The emergence of new races of stripe rust, threat posed by *Ug99* race of black rust, and foliar blight incidence to newer areas will require change in selection of parental lines, varietal promotion criterion and exercising selection pressure under natural hot spot locations for developing better varieties with wider stability and adaptability.

Survey and surveillance activity need to be expanded to cover more area so that the monitoring of diseases and insect-pests can be done more effectively. The emergence of new races/virulence can be known within a short time through such program at regional level. In the wake of new RCTs, there is a need to breed varieties suited to different tillage conditions particularly for double cropping pattern (Rice-wheat) in South Asia. Besides, laser land levelling should be popularized to economize the use of water and nutrients (Anonymous 2013).

The futuristic research approaches under crop improvement so as to improve yield potential, disease resistance, tolerance to abiotic stresses, nutritional and end-product quality for making good quality noodles, biscuits, pastas, breads and chapatis calls for a sound and focused research programme. The increase in temperature will be a major threat resulting in increased abiotic and biotic stresses of new dimensions. Hence, breeding strategies will have to be reoriented to develop wheat varieties which are tolerant to temperature fluctuations and have resistance to new virulent diseases and pests. Therefore, concerted efforts on the part of researchers, extension workers, farmers and policy makers are needed to improve soil health, input use efficiency and the yield potential of wheat crop.

End use quality improvement: Improvement in the income of the people has accelerated the demand of specific quality products. Consumption of western style food like cookies is increasing in China and India while consumption of flat breads and flour noodles are becoming popular in western countries. The demand of high quality products like noodles, pasta, couscous and flat breads is increasing quickly around the globe. More over around three billion people on the globe are affected by micronutrient deficiency causing serious health problems including obesity and celiac disease. Therefore the challenge is to satisfy the demand of the people of various strata, i.e. under nourished people and as

well as low calorie demanding people. Gluten protein is the main determining factor of wheat end use quality. Granule bound starch synthase (GBSSI) is responsible for amylase synthesis in grain. Starch pasting viscosity affects the eating quality of wheat flour noodles. Increased starch-swelling power and desirable noodle softness have been associated with the absence of GBSSI controlled by a gene on chromosome 4A (Ross *et al.* 1996). Flour yellowness is undesirable for producing breads and Asian flour chapati but in contrast high concentration of yellow carotenoid are highly desirable in durum wheat semolina for good pasta products.

The information about the genetic control of allelic variants of main traits is necessary for efficient quality improvement. However these traits are highly influenced by the genotype×environment interactions (Eagles *et al.* 2002). The flour sedimentation test, NIRS and mixigaps are important tests. Rapid, non-destructive and small scale tests including MAS, NIRs and dough rheology will if applied at different stages of breeding for quality wheats. It is necessary to identify genotypes combining stable yield and quality traits across the environments (Anonymous 2014).

A HOLISTIC AND FARMERS FRIENDLY APPROACH FOR ENHANCING YIELD

It is important to recognize that for farmers, maximizing yield is not their sole objective; profitability and managing risk are more important criteria. Delivering increased yields is a complex challenge that is unlikely to be solved by a single approach. There are three specific major challenges: increasing yield potential (the maximum yield for a given genotype under optimal conditions), protecting yield potential, and increasing resource use efficiency to ensure sustainability. In regions with high production, albeit low productivity, for example, the United States of America, China, or India, doubling or even small gains in yield would have a substantial impact on world food production.

Improvements on these figures should be achievable, and in China and India in particular, improved crop management practices will undoubtedly increase yield in the future. In the United States of America, crop genetic improvement is more likely to be required for improved yield. The considerable target of doubling wheat yields in Europe, where yields are already 5.26 tonnes/ha on average, represents a massive challenge to breeders to improve intrinsic genetic productivity. China has seen a steady increase in productivity over the past 20 years. To continue this trend, the fastest and most practical routes to increase yield are to improve agronomy (i.e. soil and crop management practices), in conjunction with countries.

The biggest gains will come from combinations of improved crops and improved agronomical practices (Fan *et al.* 2012). Knowledge of changes associated with advances in crop productivity is essential in understanding yield limiting factors and developing strategies for future genetic improvement (Singh *et al.* 2010, Sharma *et al.* 2013). The most common approach has involved retrospective studies

consisting of a direct comparison of old and modern varieties grown simultaneously in dedicated trials. There exists a vast potential of achieving the target production of wheat, provided research and developmental efforts are carried forward in right direction.

STABILIZING YIELD AGAINST ENVIRONMENTAL CHANGES

A prerequisite for high-yielding varieties is trait stability, particularly yield and quality attributes. Traits need to be robust on a year to year basis and across a range of environments. In many regions, year to year variability in yields can be significant. Generally, farmers prefer guaranteed minimum productivity rather than a gamble on high yields with the alternative being very poor yields. Stability of production and the consequent influence on markets is also to be preferred on a global scale.

To cope with emerging challenges of natural resource degradation, escalating input costs and declining farm profits while improving the productivity, the new agronomic management practices based on the elements of conservation agriculture and precision farming have shown promise under different production systems in diverse ecologies and farming situations. However, there has been significant genotype \times management interaction which many a times limit potential gains of either of components (genotype and management), if they are not compatible. Therefore, tailoring genotypes for different crop management scenario and production systems should also find place while reorienting breeding strategies to capture genotype \times management interactions.

The synergy of disciplines for new science is required so as to achieve the projected demand of wheat in time to come. The Indian wheat programme has required infrastructure, manpower and new tools and is capable of meeting the future challenges (Anonymous 2013). It can be concluded here that to counter the possible effects of global climatic variations, integration of approaches including conventional breeding, modern biotechnological tools, resource management techniques of agronomy and regular survey and surveillance for monitoring the incidence of pests and diseases will be the key issue in shielding wheat crop against climatic vagaries and thereby ensuring food security for the ever increasing population of the country.

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