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1 Acknowledgments

We would like to acknowledge the research and technical teams at The Plant Breeding Institute (PBI) of The University of Sydney, the Indian Institute of Wheat and Barley Research (formerly the Directorate of Wheat Research) (IIWBR), the Punjab Agricultural University (PAU), the Bihar Agricultural University, Sabour (BAUS) and the Birsa Agricultural University, Ranchi (BAUR) for their assistance and advice at all levels of this research. We also acknowledge the network of Indian researchers who managed the Advanced Variety Trial network across India. Their commitment to providing high-quality data across many locations made the conclusions of this work possible. We also acknowledge the 10-year funding provided by ACIAR which made it possible to realise real impacts. Such long-term funding made it possible to take this research from concept to delivery. We also acknowledge the funding and support of ICAR which made it possible for Indian researchers to continue to engage with this program through joint Phase 2 funding. Finally, we acknowledge the vision and leadership of two ACIAR program managers; Dr Paul Fox and Dr Eric Huttner, who saw the need for this research and kept faith in the team.

2 Executive summary

"Molecular marker technologies for faster wheat breeding in India" was a 10-year program, initiated in 2007, that aimed to integrate molecular technological advances with practical wheat breeding at key institutions in India. The program, funded initially by ACIAR (2007 – 2013; Phase 1) and then jointly by ACIAR and the Indian Council for Agricultural Research (ICAR) (2013 – 2017; Phase 2) was highly successful in augmenting a step change in breeding practice. Initially, the program focussed on molecular markers for simply inherited traits such as rust resistance with partners in north-western India. Parents were characterized, crosses optimised, progeny selected efficiently using marker assisted selection, data managed using a relational database and a unique Indo-Australian wheat germplasm developed. The Phase 2 program extended these benefits to eastern India while implementing a genome wide selection approach for complex traits such as yield in northwestern India. The program culminated in the release of PBW723, the first wheat cultivar released in India developed using molecular technology. In addition, extensive analysis of multi-environment trial data and associated genetic information has provided a genetic blue-print for yield potential to assist all Indian wheat breeders now and into the future.

3 Background

In the mid-2000s wheat production in India had been static after a peak in 1999 of 76.4 million tonnes. It was recognised that as industrial and urban development increases, the land area and water available for cropping will fall. One of the causes of the falling wheat production was the decline in the yield of the variety PBW343 which was grown in more than 90% of the Punjab agricultural area (approximately 4.3 M ha) in 2006. This cultivar was susceptible to new stripe rust virulence in the Punjab. It was recognised that maintenance of yield at the former level of PBW343 alone would benefit for the Indian economy and regional food security.

In many countries, newly developed molecular tools and techniques are used to accelerate plant breeding and Australia leads the world in the development and adoption of these molecular technologies in nationally coordinated programs. The bilateral research initially funded by ACIAR aimed to introduce these technologies into practical breeding programs in the most efficient and effective way possible. While excellent molecular biologists in India are spread over many institutes, their outputs are not impacting wheat breeding throughout the country. This project utilised the skills and experiences of Indian and Australian wheat breeders and researchers to implement effective and useful molecular technologies to develop improved wheat varieties. This collaboration between the Plant Breeding Institute (PBI) of the University of Sydney, the Indian Institute of Wheat and Barley Research (formerly the Directorate of Wheat Research) (IIWBR) and the Punjab Agricultural University (PAU) was successful in establishing molecular breeding in north-western India. Molecular markers for a number of diseases, morphological, phenological and quality characters were used routinely. Lines selected using molecular markers appeared in regional yield trials in India and a large amount of germplasm with unique combinations of rust resistance genes from Indo-Australian crosses were developed.

Based on a successful external review, the project entered a second phase in 2013 (CIM2013-009). The programs at IIWBR and PAU had successfully integrated molecular technologies and associated data management and were ready for the next step; molecular breeding for complex traits, particularly yield. It was also recognised that the benefits of molecular breeding should be extended to eastern India hence a partnership with Bihar Agricultural University, Sabour (BAUS) and Birsa Agricultural University, Ranchi (BAUR) was developed. This Phase 2 project was jointly funded by ACIAR and ICAR.

4 Objectives

Project aim:

The overall aim of this project is to increase the efficiency and effectiveness of Indian wheat breeding using molecular marker technology; initially for key adaptive traits and later extended to complex characters.

Project Objectives

Phase 1 (CIM-2005-020)

Objective 1. To improve the efficiency and effectiveness of parental selection and crossing in wheat breeding programs at DWR and PAU through the application of gene profiles and DNA-based diversity analyses.

Objective 2. To use molecular technology to pyramid effective rust genes in key wheat backgrounds to develop the critical parental genotypes required by the applied wheat breeding programs.

Objective 3. To implement large scale MAS in the Indian wheat breeding programs at DWR and PAU to more efficiently develop high yielding wheat lines with improved resistance to stem, leaf and stripe rust.

Objective 4. To establish ICIS at PBI and NRCPB and to use ICIS to capture and manage molecular, phenotypic and pedigree data, initially through implementation at PBI Cobbitty and NRCPB and then at PAU, DWR and other sites

Phase 2 (CIM2013-009)

Objective 1. Improve the efficiency and effectiveness of parental selection and crossing in wheat breeding programs at DWR, PAU, BAUS, BAUR and PBI.

Objective 2. Use molecular technology to pyramid adaptive genes in key wheat backgrounds to develop the critical parental genotypes required by the applied wheat breeding programs.

Objective 3. Implement large scale modern MAS in the Indian wheat breeding programs at DWR and PAU to more efficiently develop high yielding wheat lines with the appropriate agronomic traits.

Objective 4. To maintain ICIS (or a suitable data storage and management system) and the Integrated Breeding Platform breeding tools at PBI and DWR to capture, manage and analyse molecular, phenotypic and pedigree data

5 Methodology

Phase 1 (CIM2005-020)

Markers available for a range of traits including rust resistance genes were validated locally in India and used to characterize the parental materials and F1 combinations. The parents were also genotyped using DArT as were key Australian materials. Molecular biologists from DWR and PAU visited Canberra to study the DArT technique.

Key rust genes (Yr10, Yr15, Lr35, Lr37) were then backcrossed into six Indian cultivars in a collaborative effort between DWR and PAU with the aim of combining one leaf rust and one stripe rust gene. This parent building continued targeting stem rust. Sr2 was combined with any two of Sr24/Lr24, Sr25/Lr19, Sr26, Sr36/QYrCk2/LrCk and Sr39/Lr35. Leaf rust genes Lr34/Yr18 and Lr46/Yr29 were combined with any of Lr35/Sr39, Lr24/Sr24, Lr37/Sr38/Yr17. Stripe rust combinations targeted included Yr18/Lr34 and Yr29/Lr46 combined with any of Yr15 + Yr24 (coupling in Avocet), Yr10 and Yr17/Sr38/Lr37. Doubled haploids were used strategically to advance this work.

Laboratory facilities and equipment at IIWBR and PAU were able to manage up to 15,000 DNA extractions and associated marker assays per year per program. The International Crop Information System (ICIS), co-developed by a number of international partner organizations including CIMMYT and the International Rice Research Institute (IRRI) was used to warehouse and share data with limited success due to software shortcomings.

Strategic molecular marker development for rust genes effective under Indian conditions using existing populations was conducted and the markers were used in MAS at the later stages of the project. Existing RILs or double-haploid populations were phenotyped and genotyped to promote this process.

Implementation of MAS required modification of breeding methods and population handling techniques. In the process, a unique Indo-Australian germplasm was produced and the derivatives made available to wheat breeders in both countries.

Phase 2 (CIM2013-009)

New marker/trait associations identified in Australia and of relevance to eastern Indian programs (primarily rust resistance, aluminium tolerance and grain quality) were optimised at PBI and extended. The Breeding Management System (BMS) was adopted as a replacement for ICIS and a training workshop held in India. Training in the development and implementation of double haploidy was also conducted in Bihar. Dr Howard Eagles collated the extensive Indian phenotypic data from national wheat Advance Variety Trials (AVT) with the help of local scientists. These data, including information already captured and available in the central ICIS database at DWR, were used to conduct an extensive analysis of wheat adaptation in India (see publications) and to identify key genomic regions linked to yield potential. These were validated in unrelated Indian materials. Fee-for-service 35K SNP genotyping was established in New Delhi and the service used by the project to genotype all AVT entries. A series of male sterile materials based on key Indian cultivars were made at the PBI to facilitate recombination based on QTLs of small and large effect. Other activities with an Indian focus only such as waterlogging and quality breeding continued using both phenotyping and genetic information as appropriate.

6 Achievements against activities and outputs/milestones

Objective 1: Phase 1. To improve the efficiency and effectiveness of parental selection and crossing

no.	activity	outputs/ milestones	completion date	comments
1.1	Characterize parents for known genes (PC and A)	Known gene profiles completed. Data used to make crosses	June – August 2007	This is an on-going breeding activity
1.2	Characterize background diversity of parents (PC and A)	DArT profiles completed and used to make crosses	August 2008	This is an on-going breeding activity although SNPs now used

PC = partner country, A = Australia

Objective 2: Phase 1. To use molecular technology to pyramid effective rust genes in key wheat backgrounds

no.	activity	outputs/ milestones	completion date	comments
2.1	Develop new parents with new gene combinations (PC & A)	Materials crossed, screened using markers. Double haploids made as needed	November 2008	This is an on-going breeding activity
2.2	Develop high-throughput sample handling and tracking protocols (PC)	Intervention points in breeding identified. Lab protocols improved. Staff assigned to MAS.	November 2010	Marker work has evolved since the availability of 35K SNP in Delhi. For a high of 15,000 assays for known genes in 2010, this has dropped to more targeted marker screening of backcross progeny.
2.3	Genotype previously developed populations for rust resistance (PC & A)	Materials genotyped and QTL analysis performed	November 2009	The QTL analyses identified previously mapped regions and were therefore not unique.
2.4	Phenotype a global drought mapping population for drought response at Karnal (PC & A)	Phenotypes generated over two years and QTL analysis performed	November 2010	No useful QTL were identified under Indian conditions

PC = partner country, A = Australia

Objective 3: Phase1. To implement large scale MAS in the Indian wheat breeding programs at DWR and PAU

no.	activity	outputs/ milestones	completion date	comments

2.1	Modify wheat breeding program methodology and identify optimal intervention points for MAS. (PC)	Gene frequency was optimised. Markers used to enrich in early generations and to purify parents	August 2008	This process of optimising marker use is on-going and changing with new technology
2.2	Develop high yielding rust resistant cultivars (PC and A)	Crosses were optimised using markers and allele enrichment used in early generations	June 2011	This process culminated in the release of PBW723 in 2017.

PC = partner country, A = Australia

Objective 4: Phase 1. To establish ICIS at PBI and NRCPB and to use ICIS to capture and manage molecular, phenotypic and pedigree data

no.	activity	outputs/ milestones	completion date	comments
2.1	Implement ICIS at PBI, PAU and DWR (IIWBR) with a central data base at NRCPB (PC and A)	Workshops held. ICIS established at all nodes and a central data base at NRCPB in Delhi. Data uploaded	May 2009	The first implementation was complete by March 2008 and all categories of data uploaded by May 2009. However, the system did not manage molecular data well and suffered from numerous software bugs. The BMS was later implemented (in Phase 2).

PC = partner country, A = Australia

Objective 1: Phase 2. Improve the efficiency and effectiveness of parental selection and crossing in wheat breeding programs at DWR, PAU, BAUS, BAUR and PBI

no.	activity	outputs/ milestones	completion date	comments
2.1	Extend the benefits of marker assisted wheat breeding, data management and double haploid technology into eastern India	MAS screening protocols established at BAUR and BAUS and rust marker screening initiated. Haploids produced	Jun 2015	Protocols were established (and relevant primers exchanged) for known genes in the east. Double haploid training was conducted at BAUS and haploids were produced. However, problems were encountered with doubling.
2.2	Provide a conduit between technology external to IAP-MAWB and the wheat breeding programs at DWR, PAU, BAUS and BAUR	Markers for Yr51, Yr4 (allele), Sr56, Lr52/Yr47 plus other effective genes used in appli Consensus SNPs linked to key rust genes identified and confirmed	June 2015	These activities are on-going and materials continue to be developed.
2.3	Estimate gene effects for key traits using historical phenotyping and associated molecular data	AVT data collated and analysed and the materials genotypes. GWAS completed and key SNPs tracked in breeding	June 2017	The delay in ICAR funding (almost 2-years) limited this component. However, the MET analysis and GWAS were completed and a molecular blue-print for yield established. These materials are being crossed beyond the end of the project.

PC = partner country, A = Australia

Objective 2: Phase 2. Use molecular technology to pyramid adaptive genes in key wheat backgrounds to develop the critical parental genotype

no.	activity	outputs/ milestones	completion date	comments
2.1	Continuation of the evaluation and development of Indo-Australian materials	The process of parent selection, crossing, MAS, double haploidy continues including local training in India.	December 2013	These activities are on-going.
2.2	Integrate the activities with the Indian led water-logging, grain quality and rust projects	New marker trait associations identified and crossed in the key breeding programs	June 2014	The waterlogging and quality projects did not identify new QTLs. This was largely due to a lack of Indian resources to genotype and map these populations. However, adult plant stem rust resistance genes that were mapped on chromosomes 2B and 5D were transferred to two Australian and two Indian wheat cultivars through marker assisted selection.

PC = partner country, A = Australia

Objective 3: Phase 2. Implement large scale modern MAS in the Indian wheat breeding programs at DWR and PAU

no.	activity	outputs/ milestones	completion date	comments
2.1	Introduce a genomic selection scheme for complex characters, primarily targeting yield, at DWR and PAU.	Develop a training population, genotype and phenotype it, estimate gene effects, calculate genomic estimated breeding values and recombine these using male sterility to facilitate recombination.	December 2017	The data was collected and upload into a relational database for yield (as of June 2014) for 5 years of AVT. This was considered the training population. Marker data on known genes was provided by IIWBR in 2015 and these are loaded into the Access database. A local provider for SNP genotyping was contracted and a 35K SNP genotype of AVT materials generated in April 2016. Given the extensive delays in ICAR funding, a GWAS was conducted and four genomic regions linked to yield identified. Male sterile lines were developed but the planned recombination will take place outside the project.

PC = partner country, A = Australia

Objective 4: Phase 2. To maintain ICIS (or a suitable data storage and management system) and the Integrated Breeding Platform breeding tools at PBI and DWR to capture, manage and analyse molecular, phenotypic and pedigree data

no.	activity	outputs/ milestones	completion date	comments

2.1	Maintain linkages and data flow between local data management at IIWBR, PAU, BAUR, BAUS and PBI and the central data management project at IIWBR	BMS implemented at all nodes following training.	June 2014	BMS is implemented at all nodes (stand- alone) and web accessible versions available on the IIWBR and USyd servers. All project partners (including other IAP partners) have been trained and the data stored. However, implementations at BAUR and BAUS have not progressed and direct access to the IIWBR server has been denied.
2.2	Implementation of molecular breeding tools in the Integrated Breeding Platform to improve decision making in India and Australia.	Training in the use of BMS tools extended to all partners	December 2015	A workshop was conducted in December 2015 with all project partners in attendance except BARI. BARI was not included as Dr Saker was not available.

PC = partner country, A = Australia

7 Key results and discussion

Phase 1 (CIM2005-020)

Molecular marker assays were used strategically to target specific gene combinations such as Yr10, Yr15, Lr24 and Lr28 and many lines combining these four genes (and others) were developed with some yielding 10% or more above the local check. Many lines were developed using marker assisted selection and this work culminated in the release of PBW723, the first wheat cultivar released in India developed using marker assisted selection. Molecular markers are now used widely across both IIWBR and PAU wheat breeding programs and are an integral part of the breeding process. Many new lines thus developed are in all stages of yield evaluation including the national AVT.

A unique Indo-Australian germplasm was developed and shared with all partners. These materials have been used in crosses in both India and Australia by local wheat breeders and many continue to be evaluated in multi-environment yield trials. The ICIS database was implemented at all nodes and used to manage pedigrees and some phenotypic data. The central database in New Delhi was converted to MySQL from Ms Access to improve capacity (a limitation highlighted in the last report) and data from each partner was uploaded. However, the utility of ICIS was questionable and many bugs in the software hampered progress. The Integrated Breeding Platform evolved from ICIS and the Breeding Management System (BMS) was adopted to manage project data.

In summary, all Phase 1 milestones and goals were achieved and each partner was enthusiastic about extending this knowledge to the genetic improvement of more complex traits.

Phase 2 (CIM2013-009)

The Phase 2 jointly funded ACIAR/ICAR project was initially hampered by delayed payment of the ICAR funds to Indian project partners. These funds became available nearly 2 years after the commencement of Phase 2 and led to a re-adjustment of activities and timelines.

Nevertheless, Phase I project materials continued to be developed and tested at all four Indian nodes (IIWBR, PAU, BAUR and BAUS). However, the implementation of MAS at BAUR and BAUS was delayed and while MAS was established at both centres the scale of implementation fell short of original expectations.

An analysis of 5-years of AVT data was completed (see attachments) and a local fee-for-service provider (Imperial Life Sciences) was contracted by IIWBR to produced 35K SNP genotypes on all AVT materials and a more recent set of materials for validation. A genome wide association analysis identified 4 key genomic regions linked to yield in India (see attachments). A workshop was held at IIWBR in December 2015 with Breeding Management System (BMS) trainers and the Australian project team in attendance (see attached photo). BMS was loaded onto the Karnal server and all project participants trained in its use. The aim was to have the entire ICAR project network access and use BMS through the Karnal server. Problems with overheating of the Karnal server in summer required that the equipment be re-located. As of the production of this final report local Indian project partners still do not have general access to the Karnal server.

The waterlogging, rust and grain quality projects managed by India continued to develop materials and used MAS where and when appropriate.

Several elite Indian cultivars and breeding lines, converted into the blue aleurone (Bla) male sterile system in preparation for genomic selection, were purified and multiplied. These materials were to be used to facilitate recombination once validation genotypes were identified from genomic analyses. However, given the funding delays described above these were not required within the term of the project. Close to 1000 new Indo-

Australian lines, parents and checks were evaluated for yield in Australia during Phase 2. Some of these Indo-Australian genotypes produced yield up to 112% of the best industry standard (Suntop) for the northern Australian grains region. These materials were shared with local Australian breeding companies and have entered their crossing and selection programs.

8 Impacts

8.1 Scientific impacts – now and in 5 years

New wheat lines, including the release cultivar PBW723, were developed using molecular technologies provided by this project. A pipeline of new materials developed using MAS is available with materials at all levels of yield testing (ie. between station trials and the national AVT). The impacts of this project will continue for years to come as this pipeline is evaluated and materials are release to farmers. The historical AVT analysis improved our understanding of wheat yield and adaptation in India (Trethowan et al, 2018). Key locations were identified that could be used by ICAR to better target national testing and the current zonal classifications for wheat could be adjusted to better reflect the underlying environment type. Genome wide association analysis identified 4 key genomic regions and associated SNP markers that can be targeted in on-going wheat improvement. These markers represent a genetic 'blue print' for yield in India. The results are currently being validated in unrelated materials following which thy will be published. Four PhD programs (3 on-going) were established and three of these scientists will improve India's capacity in molecular breeding. The other will return to Bangladesh on completion.

8.2 Capacity impacts – now and in 5 years

Many India scientists were trained at different levels during the course of the project and many of them were female.

The males include Mandeep Randhawa – he completed his PhD (JAF) and is now leading Ug99 screening in CIMMYT, Kenya. Mahbub Rahman is completing his PhD (JAF). He will finish mid-2018. Deppak Baranwal (JAF), he enrolled for PhD in 2017. Vikas Venu Kumaran – (IARI RRS, Wellington) – spent 2.5 months at PBI and received wheat rust pathology/genetics/MAS (and attended the International Wheat Conference and BGRI technical Workshop 2015 in Sydney). Om Prakash Gangwar (IIWBR RRS, Shimla) – spent 2.5 months at PBI and received wheat rust pathology/genetics/MAS (and attended the International Wheat Conference and BGRI technical Workshop 2015 in Sydney). Hanif Khan - (IIWBR RRS, Shimla) – spent 2.5 months at PBI and received wheat rust pathology/genetics/MAS. He came under endeavour fellowship.

Females include Puja Srivastava (PAU, Ludhiana). She was trained at PBI in doubled haploid production and wheat rust pathology/genetics/MAS. Dr Rekha Malik (ICAR-IIWBR, Karnal) was trained under the Australia Awards funding, her nomination came through CIM2007-084 project interaction with Dr Indu Sharma (then Director IIWBR). Dr Jaspal Kaur, wheat pathologist PAU, was mentored during Australian team visits to PAU in the final five years of the project. Ritika Chaudhary (JAF). She is completing her PhD and is due to finish mid-2018.

In addition, numerous workshops, particularly on data management were arranged in India with the Australian team and special database trainers in attendance.

8.3 Community impacts – now and in 5 years

Community impact will be realised once higher-yielding, more resilient cultivars are released for cultivation. This process has begun with the recent release of PBW723. These new cultivars will improve family income and stimulate economic activity within regional communities if they represent and improvement in yield and sustainability (through more effective and durable rust resistance). Breeding pipelines full of these materials will ensure that this impact occurs well beyond the close of the project.

8.3.1 Economic impacts

Primary economic impacts will accrue when the higher yielding lines developed under this program are grown by farmers. This is now underway with the release of PBW723. We expect the initial economic impacts to be realised beyond the close of the project in 2017 (initially through lines currently in the Indian AVT trials but later as contributions to the pedigrees of Australian cultivars).

More immediate impacts will accrue from the more efficient use of information and resources through the full implementation of the web-based BMS version 4 if permission is given to the wider ICAR wheat network to access BMS on the IIWBR server.

8.3.2 Social impacts

Social impacts will accrue from increased income generated through the economic impacts of the new cultivars. These cultivars may have better disease resistance and improve quality which will increase their value to farmers and consumers. Increased income is expected to increase the participation of disadvantaged groups in rural communities in education and other forms of advancement. These impacts will be realised after the close of the project.

8.3.3 Environmental impacts

The improved rust resistance of new cultivars developed under this program carrying targeted combinations of rust genes will remove the need to apply fungicides: an increasingly popular practice is north-western India. The reduced fungicide use will have benefits across the farming system including reduce chemical residues. This impact can be realized in the short, medium and long term. New genes identified in the project were integrated in new materials (the first released as PBW723) and many others are under consideration for release. New genetic diversity continues to be crossed and selected using MAS at all nodes

8.4 Communication and dissemination activities

Annual project meetings were held in India each year and the results of all partners presented and discussed. Trethowan, Bariana and Bansal visited India each year of the project and conducted separate meetings with the teams at each node. Australian wheat breeders and pre-breeders were invited to attend a field day and germplasm selection day at PBI's northern node at Narrabri in October 2015, 2016 and 2017. Indo-Australian project materials were on display and talks were given by Trethowan on the project and germplasm outcomes. Significant numbers of new Indo-Australian lines were requested by local Australian wheat breeders. Trethowan communicated the outcomes of this project at various national and international meetings over the course of the project including the International Wheat Conference in St Petersburg and the Southern African Plant Breeding Conference in Stellenbosch.

9 Conclusions and recommendations

9.1 Conclusions

The 10-year program was highly successful in achieving the overall goal of speeding up the wheat breeding process in India. New technologies were effectively and efficiently introduced and implemented and now comprise an integral part of the participating Indian wheat breeding programs. While some may argue that these changes may have happened anyway, it is clear from the testimony of the local breeders that the project provided the impetus for change. The breeding programs involved are now much more efficient and better placed to continue to adopt new technologies. The project led to the release of the first wheat cultivar in India that was developed using molecular markers and full breeding pipelines of materials will ensure on-going impact. Many scientists were trained both at post-graduate level and through participation in workshops (primarily on data management) and training visits to the PBI. While the project was successful, there were difficulties encountered over the 10-year period and most of these related to delays caused by the Indian bureaucracy. These limitations delayed the transfer of materials, limited travel for some participants and significantly delayed the funding for Indian partners in Phase 2, such that the Indian and Australian activities were not synchronised as planned.

9.2 Recommendations

- The program was highly successful yet the communication of this was obscured. This is primarily because the work was conducted within existing breeding programs that received local government funding as well. In future, budget to promote communication of outcomes should be provided.
- The exchange of germplasm was generally one way with the Australian collaborators exchanging materials on time. Clear protocols were established for the exchange of experimental germplasm in the original agreement and these were not always honoured in a timely way. Any future agreements should be explicit on what will be exchanged and firmly time bound.
- The management of data using the BMS should continue at all nodes. IIWBR should grant access to local collaborators to their central BMS database so that information and data can be easily exchanged.
- The outcomes of the genomic analysis of the Advanced Variety Trial should be used in breeding to enhance yield. More years of AVT should be included to improve the accuracy of predictions.
- The blue aleurone (Bla) male sterile system has been introduced to Indian wheat cultivars. This was initially to promote recombination of the marker effects identified through genomic selection. However, these materials can also be used to produce F1 hybrids to exploit heterosis. The development of a new multi-lateral project (including partners in Bangladesh) to exploit this technology is recommended.

10 References

10.1 References cited in report

10.2 List of publications produced by project

Trethowan Richard, Ravish Chatrath, Ratan Tiwari, Satish Kumar, MS Saharan, Navtej Bains, V S Sohu, Puja Srivastava, Achla Sharma, Nitish De, Surya Prakash, G P Singh, Indu Sharma, Howard Eagles, Simon Diffey, Urmil Bansal and Harbans Bariana. 2018. An analysis of wheat yield and adaptation in India. *Field Crops Research*, 219: 192-213.

Sohail Younas, Urmil Bansal, Harbans Bariana, Parveen Chhuneja, Abdul Mumtaz, Atiq Rattu, Richard Trethowan. 2014. Identification of an Lr28-linked co-dominant molecular marker in wheat. *Australian Journal of Crop Science*, 8:1210-1215.

11 Appendixes

11.1 Appendix 1:

There are 4 attachments to this report

1. Trethowan et al FCR (a copy of the multi-environment analysis of AVT)
2. GWAS report. A copy of the GWAS analysis
3. Workshop 2015 BMS – a photo of the team at BMS training Karnal
4. Photo of team members with the first cultivar released (PBW723)