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RESEARCH ARTICLE

Relevance of height, heading and maturity in productivity enhancement of wheat

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Abstract

Yield improvement in wheat through grain number and grain weight has become increasingly difficult in many production environments. Can the non-grain yield parameters of yield like height, flowering and maturity be explored as an alternate for further yield enhancement? This study comprehends such possibilities by analysing performance of the released and pre-released varieties evaluated in ten diverse production environments of India during the period 2000-2021. Regression analysis has highlighted relevance of these three crop expressions in wheat yield and based upon their contribution, selection criteria has been suggested for different production environments of India. Magnitude of impact varied under each environment and their collective contribution was highest in a production environment where growth condition was most favourable for wheat growth i.e., north-western plains. Increase in height and maturity duration coupled with early heading was found useful in this region for both wheat category, i.e., timely-sown and late-sown. These three yield determinants were found highly effective in timely-sown of the adjoining north-eastern plains also but under late-sown condition, prolonged heading was the chief yield predictor. Height for timely-sown and maturity for late-sown condition was most crucial for central India. Delayed heading in timely-sown and late flowering with extra height in late-sown wheat had been tipped for yield improvement in peninsular India. Delayed maturity for timely-sown and height for late-sown wheat had been suggested for productivity enhancement in the northern hills. Besides grain yield, this selection strategy based upon height and crop phenology also enhanced grain weight in certain environments. At a time when selection for grain attributes is not providing further push in productivity enhancement; it would be worth trying to explore these non-grain field indicators as selection strategy for further advancement in productivity of bread wheat.

Keywords: Grain yield, Indian wheat, non-grain yield determinants, phenology, production environments

Introduction

Wheat (*Triticum aestivum* L.) is grown under diverse agro-ecological conditions of India where growth conditions differ and so is the yield harvest. It is obvious that besides productivity, field expression must also be differing under different growth environments (Pandey et al. 2015; Sharma et al. 2019). Thus, understanding the changes occurring in the grain and non-grain yield parameters and the inter-trait relationships becomes important for further hike in yield potential of wheat. Plant phenology which describes the timing of plant development, has been acknowledged as a major aspect of plant response to the environment; therefore changing crop phenology can serve as an important bio-indicator in the era of climate change (Asseng et al. 2017; Rezaei et al. 2018). The adapted early flowering cultivars successfully advance the onset of anthesis and the enforced longer grain filling period reduces or avoids the risks of exposure to enhanced drought and heat stresses in late spring (Yang et al. 2019). Optimal height under given environmental condition is vital for adaptability, productivity and yield stability of the wheat cultivars (Bognár et al. 2007), whereas maturity duration is the major genotypic cause of genotype-environment interaction (Garatuza-Payan et al. 2018). Traditionally, grain number and grain weight have been recognized as the main constituent of wheat yield (Brinton and Uauy, 2019; Garatuza-Payan et al. 2018). The wheat breeding program emphasizes an increase in the grain

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number through better tillering and spike characteristics. In some wheat breeding centres of India, grain weight is also addressed especially in the heat tolerance focussed research programmes (Mondal et al. 2016). Still, the yield level keeps staggering and raising the yield bar even by 5-10% turn out to be a difficult proposition in majority of the region. At this juncture, it is imperative to explore the role and contribution of the non-grain parameters (NGP's) namely plant height, maturity duration and heading days. It is a general perception that adversary of climate change in wheat is first realised on NGP's and later reflected in grain yield and size of the grain. Increased height and crop duration under favourable growth condition often results in higher biomass production and accumulates more grain yield (Reynolds 1 et al. 2009). Although NGP's are influenced by the abiotic factors; genetic constitution also modulates their role in ascribing varietal differences. Therefore, it is crucial to understand whether selection exercised on these field indicators can improve the wheat yield and if so up to what extent and under which environment. Such studies attain more prominence when highly diverse production environments as observed in India. Few reports from India have highlighted variations in wheat's grain and non-grain attributes under diverse growth environments (Mohan et al. 2011, 2017). However, a comparative study was lacking to demonstrate their contribution and potential role in yield enhancement without exerting any undesired effect on grain size. Yield is expensive to pursue, therefore other objectives must be attained before wide scale yield evaluation. Indian wheat program provides a perfect platform for such investigations where high-yield genotypes of different genetic backgrounds are being tested in several productions environments for a long time. Data has been generated on plant height, days to heading and maturity duration, grain yield, and grain weight. By examining long-term yield data of Indian wheat research programme, this study aims to i) emulate differential impact of NGP's and understand the inter-relationship pattern, ii) realize their comparative contribution in grain yield, iii) suggest ways to tap their potential for further increase in wheat productivity and iv) search possibilities of simultaneous improvement in grain yield and grain.

Materials and methods

Study material involved released (checks) and pre-released (new test entries that reached final year of testing) wheat varieties evaluated in two trial series of irrigated advance varietal trials conducted by the All India Coordinated Research Project on Wheat and Barley (AICRPW&B) in five diverse zones of the country i.e. northern hills zone (NHZ), north-western plains zone (NWPZ), north-eastern plains zone (NEPZ), central zone (CZ) and peninsular zone (PZ) during the 22 year period 2000–2021. NHZ that covers hills and foothills of the Himalayas has long winter with low temperature, while NWPZ and NEPZ represent the Indo-Gangetic plains, the land of high fertility and good rainfall. Among the five zones, NWPZ is India's most productive wheat belt. Climatic conditions in this zone are most ideal for wheat growth. In comparison, winter is short and the climate is normally humid in the adjoining NEPZ. Wheat crop in CZ often faces soil moisture stress and high temperature as the climate is hot and dry in this part of India. Peninsula in down south, i.e., PZ has similar temperature and soil, but the climate is not that dry. Sowing of timely-sown wheat (TSW) started with the onset of winter and was mostly completed by the end of October in the hills and by the middle of November in the plains. Late-sown wheat (LSW) was planted 15–20 days after the sowing schedule of TSW. Since LSW gets a shorter life span, short duration genotypes fit in this category. Fertilizer dose in TSW was 150N:60P:40K $kgha^{-1}$ in NWPZ/ NEPZ and 120N:60P:40K $kgha^{-1}$ in the CZ/ PZ and NHZ, whereas dosage in LSW was 90N:60P:40K $kgha^{-1}$ throughout the country. No chemical was sprayed while raising the crop under these production environments.

Since the trials involved multiple test sites, the zonal mean of each test entry was derived for height (HT), days to heading (DH), days to maturity (DM), 1000 grain weight (TGW) and grain yield. DH denoted the duration of the vegetative period, whereas the difference between DM and DH represented the reproductive period or grain filling duration (GFD). Standardized data of each environment was computed for regression analysis to assess the relationship of NGP's like HT, DH, DM and GFD with TGW and grain yield. Coefficient of determination (R^2) was derived to study the relationship of NGP's individually or in combination with grain weight and productivity of wheat. The difference occurring in mean of two populations was compared by "t-test". Coefficient of variation (CV) was derived to compare the extent of variability in different parameters.

Results and discussion

Diversity in production environments

The ten production environments of the Indian coordinated wheat research programme were quite diverse in expression of grain yield, plant height and crop phenology. When a comparison was made between the zones, it was difficult to generalize the impact of height and maturity on grain yield (Fig. 1). Under timely sown conditions, a significant yield difference was obvious in NWPZ (51.2 q/ha) and NEPZ (42.3 q/ha) even when there was no big difference in the plant height (NWPZ: 94 cm, NEPZ: 92 cm). This difference in productivity can be attributed to maturity duration (NWPZ: 142 days, NEPZ: 122 days). Differences in height and maturity were quite evident between NHZ and PZ under timely-sown conditions but there was hardly any difference in wheat productivity (NHZ: 43.0 q/ha, PZ: 43.6 q/ha). Across the zones, overall productivity was highest in NWPZ and CZ and the yield levels also matched in both category of wheat i.e. TSW and LSW, even though large maturity difference was apparent in each production condition. Despite large maturity duration, the productivity of LSW was lowest in NHZ mainly because there was drastic reduction in HT (16cm) in comparison to TSW. Late-sown trial in NHZ is also conducted under limited irrigation and the germination is often quite erratic. This comparison underscores that wheat productivity does not commensurate with height and maturity in the same manner under varying agro-climatic conditions. Influence of NGP's on wheat productivity cannot be adjudged from differential wheat expression noticed under varying environments. It helps to understand characteristic features of wheat expression in different production environments.

Divergence in NGP's inter-relationship

Association between the NGP's varied in different production environments according to the variability noticed in the study material and climatic conditions. The relationship between DM/ DH and HT was totally missing in TSW of NHZ and LSW of NWPZ (Table 1). Variations in the pre-anthesis period had no significant impact on HT in such environments. DH was correlated positively with DM and negatively with GFD under all conditions but the strong association between DM and GFD was not realized in TSW of NWPZ, NEPZ and CZ. It was an indication that variations occurring in maturity duration might not have induced any shift in GFD in such environments. It is evident that if certain associations that are so obvious otherwise (like relationship between HT and DM; DH and HT) fail to establish despite comparable variation level (CV); it is fair enough to assume that the trend did not exist under those growth environments. Every production environment has certain unique NGP relationships that account for differential impact on grain formation and development.

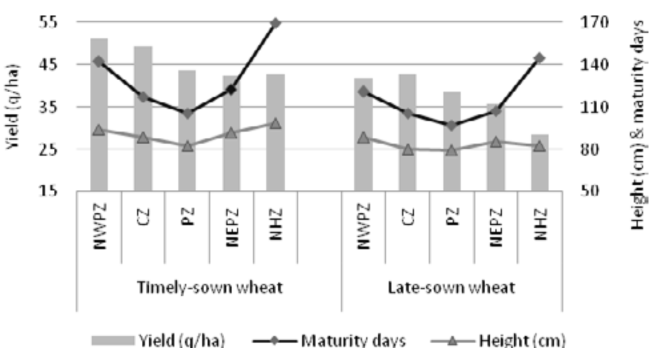

Fig. 1. Comparison of wheat yield, height and maturity days in different production environments

NGP relationship with grain yield

Maturity duration and plant height are slated to have strong positive effect on the wheat yield. Both the traits are influenced by the genetic (vernalization, dwarfing and photoperiod insensitive genes) as well as non-genetic parameters like crop management and weather conditions (Saiyed et al. 2009). It was quite obvious that wheat productivity differences in different environments occurred mainly because the duration to complete the life cycle differed. Due to diverse production environments and genetic makeup of the test entries; differences in yield and maturity duration were quite large in the Indian wheat. So many variations must have occurred climatically and different plant types must have been tested in every production environment during this big time frame of 22 years. Fluctuations in weather conditions and diversity in the tested material must have recorded different levels of variations in the grain and non-grain attributes. Any study based upon this diverse and large population is sufficient to authenticate relevance of NGP's in productivity of Indian wheat.

Regression analysis between yield and individual NGP's made it amply clear that NGP's also played important role in regulating the yield potential (Table 2). R^2 value derived in regression analysis reflects level of association between the two variables. In view of differential relationship amongst the NGP's, their impact on wheat yield varied in different growth conditions. Differences in R^2 value revealed that the magnitude of association between NGP's and grain yield differed in each environment. Amongst all environments, it was only TSW of NWPZ where every NGP established significant relationship with grain yield. It simply means that when growth conditions are favourable in a given environment, number of NGP's associated with yield also popup. There was no NGP which could establish relationship with yield under all conditions and the least important

Table 1. Correlation coefficient between NGP's under different production environments

Relationship	Timely-sown wheat					Late-sown wheat				
	NWPZ (128)	NEPZ (142)	CZ (62)	PZ (73)	NHZ (99)	NWPZ 126)	NEPZ (90)	CZ (95)	PZ (83)	NHZ (62)
DM~HT	0.61**	0.31**	0.44**	0.34**	0.20	0.10	0.40**	0.46**	0.32**	0.37**
DM~DH	0.73**	0.77**	0.77**	0.78**	0.62**	0.57**	0.49**	0.71**	0.53**	0.63**
DM~GFD	0.09	-0.03	-0.07	0.55**	0.41**	0.35*	0.58**	0.26*	0.60**	0.29*
DH~HT	0.54**	0.21*	0.50**	0.26*	0.12	0.08	0.22*	0.62**	0.26*	0.18
DH~GFD	-0.62**	-0.66**	-0.69**	-0.09	-0.46**	-0.57**	-0.42**	-0.50**	-0.36**	-0.57**

Figure in parenthesis indicate number of observations; * and ** denote significance at *P* 0.05 and 0.01, respectively amongst them was GFD.

Wheat productivity in NWPZ matched with CZ, but huge difference could be seen in the impact of NGP's. It ascertained that the variations created in NGP's through scientific interventions and natural climatic variations were exploited to high capacity in NWPZ-TS environment whereas prospects of exploiting such variations were rather limited in CZ (Fig 1 and Table 2). Relevance of individual NGP under NWPZ-TS environment was very high in case of HT (R^2: 0.45) and DM (R^2: 0.37). Highest R^2 value recorded in TSW of all other zones was 0.15, noticed for HT in CZ, DH in PZ. In LSW, however, $R^2 \geq 0.20$ could be noticed for HT in NHZ and DM in NWPZ/ CZ. It is important to mention that the relationship (R^2 value) established with the NGP's cannot be compared with the relationship of yield with grain number or grain weight, the two major constituents of wheat productivity. Still, if any NGP registers R^2 value ≥ 0.15 with high significance level, its relevance in wheat productivity cannot be overlooked, and this investigation focused in channeling these properties for improvement in wheat yield. Further, the irrelevance of a given NGP in grain yield cannot be attributed to lack of variability; it can also happen when the direct effect of a given component is marginal.

Although several reports point relevance of GFD in grain development (Wu et al. 2018), its positive contribution in yield could only be cited in the northern plains of India, especially in TSW of NWPZ, NEPZ and LSW of NWPZ. It's not as if GFD had no role in other environments, but the variations in GFD were more frequent in such environments. It pointed out that variations occurring in DM might not have induced any shift in GFD in such environments. Every production environment has certain unique NGP relationships that account for differential impact on grain formation and development. Synergy was also noticed when DH and GFD were regressed together in NWPZ and NEPZ as DM turned highly significant even though individual impact of HD or GFD was not high. It underlines that an increase in DH can lead to better grain bearing in northern India, but higher yield gain can only be achieved when proper GFD is available. Similarly, enhanced GFD might fail to deliver good yield if early flowering shortened the vegetative period.

Collective impact of NGP's on grain yield

Multiple regression analysis revealed that composite impact of NGP's on wheat yield was significant in each production environment but the magnitude (R^2 value) varied from 0.09 to 0.64 (Table 2). R^2 value underlines percent variations in yield associated with a given NGP or group of NGP's. In comparison to individual NGP, combination of these factors was more beneficial in certain production environments. This impact was highest in NWPZ in both categories of wheat and lowest in TSW of NHZ. In most congenial wheat growing environment of the country i.e., NWPZ-TS; even 64% yield variations could be accounted by NGP's alone.

In contrast, their contribution was limited to just 9% under NHZ-TS environment. 16 to 33% variations in grain yield were accrued through NGP's alone in all other environments. Cold stress levels vary each year in the hilly region, which enforces severe yield fluctuations. High R^2 value does not indicate that TSW of NWPZ could best use the climatic conditions for wheat growth. It could also have happened because of the desired genetic variations created in NGP's through wheat breeding. Variations derived through the scientific interventions can be spotted in the wheat genotypes developed in this region for height and phenological expressions. Emphasis in this region is also given to effective tillering, which influences height, heading, and maturity. Countrywide plotting of grain yield against maturity period (N: 960) illustrated that NWPZ-TS environment was distinct indeed as entries developed and tested in this environment (maturity: 142 ± 4 days) form a separate cluster altogether (Fig. 2). Entries of the maturity range noticeable in NHZ were found scattered in another cluster. Irrespective of the production condition, all test entries pertaining to the Indian plains (except NWPZ-TS) got accommodated in single cluster.

Selection strategy to harness grain yield through NGP's

Diverse production environments necessitate a special wheat improvement strategy. When wheat is touching yield plateau in many production environments, it is pertinent that vista of non-grain plant attributes is also reviewed. Breeders do keep an eye on these aspects while exercising

Table 2. Relationship of individual NGP with wheat yield in different production environments of India

Parameter	Coefficient of determination (R^2)									
	Timely-sown wheat					Late- sown wheat				
	NWPZ	NEPZ	CZ	PZ	NHZ	NWPZ	NEPZ	CZ	PZ	NHZ
HT	0.45^{***}	0.10^{***}	0.15^{***}	0.03	0.00	0.10^{***}	0.02	0.14^{***}	0.09^{**}	0.20^{***}
DH	0.06^{**}	0.01	0.06^{*}	0.15^{***}	0.04^{*}	0.02	0.11^{***}	0.11^{***}	0.16^{***}	0.08^{*}
GFD	0.12^{***}	0.05^{**}	0.05	0.00	0.01	0.11^{***}	0.00	0.03	0.01	0.03
DM	0.37^{***}	0.12^{***}	0.02	0.12^{**}	0.09^{**}	0.22^{***}	0.08^{**}	0.24^{***}	0.08^{**}	0.03
All NGP's	0.64^{***}	0.22^{***}	0.17^{**}	0.16^{**}	0.09^{*}	0.33^{***}	0.13^{***}	0.28^{***}	0.20^{***}	0.27^{***}

*, ** and *** denote significance of R^2 at $P \leq 0.05$, 0.01 and 0.001, respectively

Table 3. Multiple regression statistics of key NGP's and suggested selection criteria

Production environment	Beta value of key determinants			R^2 value	Selection criteria
	HT	HD	MAT	Key NGP's	
NWPZ-TS	0.56***	-0.53***	0.66***	0.64***	Increase in height, early flowering and late maturity
NWPZ-LS	0.27***	-0.23***	0.57***	0.33***	Increase in height, early flowering and late maturity
NEPZ-TS	0.22**	-0.34**	0.54***	0.22***	Increase in height, early flowering and late maturity
NEPZ-LS	NS	0.33***	NS	0.11**	Delayed heading
CZ-TS	0.39**	NS	NS	0.15***	Increase in plant height
CZ-LS	NS	NS	0.49***	0.24***	Late maturity
PZ-TS	NS	0.39**	NS	0.15***	Delayed heading
PZ-LS	0.21*	0.35***	NS	0.20***	Increase in plant height and delayed heading
NHZ-TS	NS	NS	0.30**	0.09**	Late maturity
NHZ-LS	0.45**	NS	NS	0.20***	Increase in plant height

*, ** and *** denote significance of R^2 at $P \leq 0.05$, 0.01 and 0.001, respectively

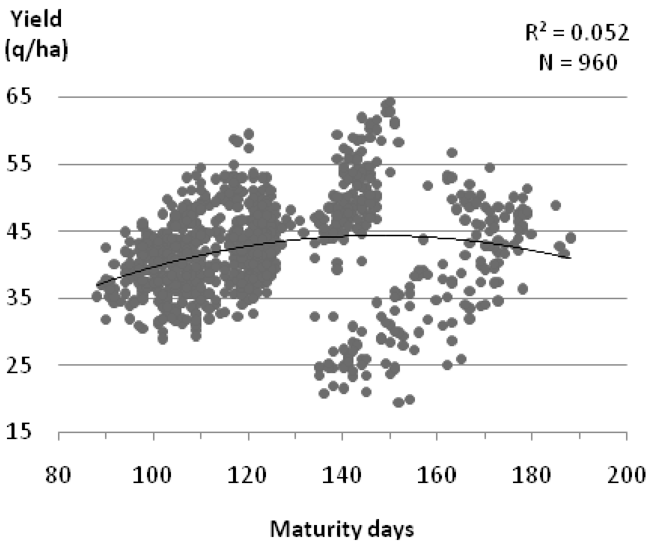

Fig. 2. Yield-maturity relationship across the wheat zones in Indian states

selection in the segregating material but which parameter is to be emphasized in a given environment is the key. Artificial intelligence gathered through this investigation offers some silver lining. It is easy to select these phenotypic traits in the field as it helps to increase biomass through plant height; grain number through enhanced vegetative phase and grain weight by adjusting the grain filling duration. Genetic variability, climatic variations and direct effect; they all matter in deciding the bottleneck factor in grain yield. It was quite evident through this study that NGP's can be exploited as yield predictor in wheat. Since their relevance is environment specific and not all NGP's count in every situation, it is important to fix the key contributors. In this endure, multiple regression analysis was restricted to only those NGP's which registered significance in this composite relationship. These key NGP's can be utilized to formulate selection criteria for further improvement in wheat productivity. For effective implementation, it is imperative to devise a strategy based upon minimum number of NGP's so that there is simultaneous gain in grain yield and weight. If not, at least there should not be a case where yield gain is harnessed with a penalty on grain weight. Based on information gathered about the key components (Table 2), simple and easy-to-adopt inference can be generated in this regard.

Identifying key NGP's make the job easy for the breeders as by applying these 1-3 indicators in the field, and significant yield improvement can be anticipated in wheat. In multiple regression analysis, R^2 value obtained through combinations like HT+DH+GFD, HT+DH+MAT and all 4 NGP's together was similar. It is only because GFD is a derived component from DM and DH. Since, it's not easy to exercise selection based on GFD in the field, this factor was excluded and the choice of determinants was limited to HT, DH and DM for identification of the key NGP's through multiple regression analysis. Key predictors identified for productivity enhancement are suggested zone-wise in Table 3.

It was clear that NWPZ was the only region where every NGP was important in TSW. Individually, HT (R^2: 0.45***) and DM (R^2: 0.37***) were very important for grain yield but in combination with DH, this association could be elated to R^2: 0.64*** (Table 2). Collectively, HT, DH and DM played a highly significant role in both categories of wheat, and the impact of DH was negative in this relationship (Table 3). It shows that selection criteria based upon extra height, delayed maturity and early heading can benefit TSW and LSW of the region. This selection strategy also benefited TGW of TSW (R^2: 0.29***). In LSW, however, the composite effect of these three NGP's on TGW was non-significant (R^2: 0.05). In the adjoin NEPZ also, height, maturity and early heading were highly useful in TSW and this combination benefitted TGW as well (R^2: 0.10***). In LSW, DH was the only driving force in NEPZ and it had no bearing on TGW. Therefore extra height, early heading and late-heading can be exploited for simultaneous improvement in grain yield and grain weight of TSW of NEPZ, whereas an enlarged vegetative period can be highly useful for grain yield of LSW.

In central India, height is only NGP that can be exploited to elate wheat productivity of TSW and it makes no significant alteration in TGW (R^2: 0.04). In LSW of CZ, DM can be a strong predictor of grain yield with no bearing on TGW (R^2: 0.00). Selection tool can be different in the adjoining PZ where DH was the lone predictor in grain yield of TSW. When coupled with HT, significant yield gain was also noticed in LSW of the region. Therefore enlarged vegetative phase is crucial for grain yield in the peninsular region. Height can provide additional benefits in LSW of PZ. Just like CZ, these NGP"s registered no significant effect on TGW. Since yield variations were quite high in NHZ due to fluctuating test sites and varying climatic fluctuations, precision might lack in the estimated benefits of NGP's. Still, selection for longer maturity duration in TSW and taller plants in LSW ensure a boost in wheat productivity of NHZ. Late maturity has no bearing on TGW of TSW in the hills, but height preference will come in aid to grain weight of LSW (R^2: 0.12^{**}).

Enrichment of wheat yield through enhanced plant height and prolonged vegetative duration had been suggested for the Indian subcontinent (Jamali and Ali 2008; Laxman et al. 2014). Reports from Pakistan and China had also emphasised selection through improved height and larger vegetative or reproductive periods (Duan et al. 2018; Khan et al. 2000; Wu et al. 2018). Advantage of height and crop phenology was also reported in some Indian environments by Mohan et al. (2017). Such phenotypic expressions are indicators of good biomass accumulation accrued from healthier vegetative growth. It is also well established that flowering in wheat depends upon accumulation of the certain amount of heat units and this had been amply demonstrated earlier in two contrasting zones of India i.e. NWPZ and CZ (Mohan et al. 2017a). In the green revolution era, reduced height was preferred in wheat breeding for a long time due to less lodging loss. Since it enforces ceiling on the plant height, the role of tall-dwarfs had also been acknowledged in the development of the high-yielding semi-dwarf wheat's (Würschum et al. 2017; Mohan et al. 2017).

This study further adds that height accompanied with unstressed maturity duration ensures higher wheat productivity in TSW of IGP i.e. NWPZ and NEPZ. In warmers areas (CZ and PZ), it is often difficult to pick genotypes which mature late as elevated temperature conditions enforce senescence in the leaves. Growth environment is equally stressful in LSW of NEPZ due to late-heat. Nevertheless, it is also well known that Sonalika, a prominent short-duration old cultivar had yield level well below the present varieties mainly because the new high-yield varieties have comparatively longer maturity duration. During last stage of this study period, all these components had been exploited in variety of development programme of NWPZ-TS. In its annual crop improvement progress report of the year 2019, AICRPW&B had reported tremendous improvement in grain yield, plant height, bio-mass accumulation, harvest index, heading days and maturity duration when growth conditions were highly conducive. If performance of four leading TSW varieties of NWPZ (HD 2967, HD 3086, DBW 88 and WH 1105) common during the crop seasons 2018 to 2020 is compared, average yield harvest was highest in 2019 (61.2 q/ha) in comparison to the previous year when it was restricted to 53.9 q/ha. It happened because there was 10 days increase in maturity duration (from 141 to 151 days) and 6 cm increase in plant height (from 98 to 104 cm). With increased height and favouring phenology, not only the yield but TGW also increased from 38.8 to 40.3 g. Compared to the 2019 harvest season, wheat yield was less in 2020 (58.0 q/ha) because there was a reduction in height by two cm and the maturity period by three days. Comparison of NGP's further revealed that genetic differences also count for differential expressions in these four high-yielding varieties. HD 3086 excelled because of longer grain ripening period (49 days) and good plant height (101 cm). HD 2967 drew advantage of extra height (103 cm) and longer maturity duration (148 days). DBW 88 had plant height (102) and maturity duration (147 days) almost similar to HD 2967 but it had the advantage of early flowering and prolonged GFD. Despite shorter maturity period (145 days) and reduced plant height (99 cm), WH 1105 was high-yielding because the crop phenology in this variety was well partitioned (HD: 98 days, GFD: 47 days).

It is amply clear that the simple and easily adoptable selection methodology suggested in this investigation can bridge some gap in the yield barrier realized not only in India but all over the world. Variability in these non-grain parameters of yield does exist in each production environment. In the past, this variation was exploited to a certain extent unknowingly. But when applied with some strategic planning, prospects of productivity enhancement can surely be improvised further. Since impact can be different under divergent environments, this study will help the wheat breeders to choose the factors required for productivity improvement in a given environment.

Authors' contribution

Conceptualization of research (DM); Designing of experiments (GS, GPS); Execution of experimental materials (GPS); Contribution of experimental material (GS); Data collection and Bibliography (HMM and RK); Analysis of data and interpretation (DM); Preparation of manuscript (DM, GS).

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References

Asseng S., Cammarano D., Basso B., Alderman P. D., Sonder K., Reynolds M. and Lobell D. B. 2017. Hot spots of wheat yield decline with rising temperatures. Global Change Biology **23**(6): 2464-2472.

Bognár Z., Láng L. and Bedő Z. 2007. Effect of environment on the plant height of wheat germplasm. Cereal Res. Commun., **35:** 281-284.

Brinton J. and Uauy C. 2019. A reductionist approach to dissecting grain weight and yield in wheat. J. Integ. Plant Biol., **61**: 337-358.

Duan J., Wu Y., Zhou Y., Ren X., Shao Y., Feng W., Zhu Y., He L. and Guo T. 2018. Approach to higher wheat yield in the Huang-Huai plain: improving post-anthesis productivity to increase harvest index. Front. Plant Sci. **9**: 1457. DOI: https://doi.org/10.3389/fpls.2018.01457

Garatuza-Payan J., Argentel-Martinez L., Yepez E. A. and Arredondo T. 2018. Initial response of phenology and yield components of wheat (*Triticum durum* L., CIRNO C2008) under experimental warming field conditions in the Yaqui Valley. PeerJ **6:** e5064. DOI: https://doi.org/10.7717/peerj.5064

Jamali K. and Ali S. A. 2008. Yield and yield components with relation to plant height in semi-dwarf wheat. Pak. J. Bot., **40**(4): 1805-1808.

Khan A. S., Khan Mk. R. and Khan T. M. 2000. Genetic analysis of plant height, grain yield and other traits in wheat (*Triticum aestivum* L.). Int. J. Agric. Biol., **2**(1-2):129-132.

Laxman V. S., Solanki Y. P. S. and Redhu A. S. 2014. Phenological development, grain growth rate and yield relationships in wheat cultivars under late sown condition. Indian J. Plant Physio., **19**(2): 222-229.

Mishra S., Singh S., Patil R., Malik A., Sareen S., Shukla R., Mishra P., Chatrath R., Gupta R. and others. 2014. Breeding for heat tolerance in wheat. Genetics, **2:** 1.

Mohan D., Singh S. and Gupta R. 2011. Vibrancy of the Indian wheat in upholding yield and quality under global environmental change. In: Singh S. S., Hanchinal R. R., Singh G., Sharma R. K., Tyagi B. S., Saharan M. S. and Sharma Indu (eds) Wheat: Productivity Enhancement under Changing Climate, Narosa Publishing House, New Delhi, pp. 87-94.

Mohan D., Tiwari V. and Gupta R. K. 2017. Progression in yield and value addition of Indian bread wheat - An analysis. Indian J. Genet. Plant Breed., **77**(1): 16-24. doi: 105958/0975-6906.2017.00003.7.

Mohan D., Mamrutha H. and Tyagi B. 2017a. Weather conditions favoring wheat (*Triticum aestivum*) productivity in hot climate of central India and congenial environment of north-western plains. Indian J. agric. Sci., **87**(1): 278-281.

Mondal S., Singh R. P., Mason E. R., Huerta-Espino J., Autrique E. and Joshi A. K. 2016. Grain yield, adaptation and progress in breeding for early-maturing and heat-tolerant wheat lines in South Asia. Field Crops Res., **192:** 78-85.

Pandey G. C., Mamrutha H., Tiwari R., Sareen S., Bhatia S., Siwach P., Tiwari V. and Sharma I. 2015. Physiological traits associated with heat tolerance in bread wheat (*Triticum aestivum* L.). Physiol. Mol. Bio. Plants, **21**: 93-99.

Reynolds M., Foulkes M. J., Slafer G. A., Berry P., Parry M. A. J., Snape J. W. and Angus W. J. 2009. Raising yield potential in wheat. Exp. Bot., **60**(7): 1899-1918.

Rezaei E. E., Siebert S., Hüging H. and Ewert F. 2018. Climate change effect on wheat phenology depends on cultivar change. Scientific Rep., **8**: 4891. https://doi.org/10.1038/s41598-018-23101-2

Saiyed I. M., Bullock P. R., Sapirstein H. D., Finlay G. J. and Jarvis C. K. 2009. Thermal time models for estimating wheat phenological development and weather-based relationships to wheat quality. Canadian J. Plant Sci., **89**: 429-439. https://doi.org/10.4141/CJPS07114

Sharma D., Pandey G. C., Mamrutha H. M., Singh R., Singh N. K., Singh G. P., Rane J. and Tiwari R. 2019. Genotype–Phenotype Relationships for High-Temperature Tolerance: An Integrated Method for Minimizing Phenotyping Constraints in Wheat. Crop Sci., **59**: 1973-1982.

Singh H. V., Kumar S. N., Ramawat N. and Harit R. 2017. Response of wheat varieties to heat stress under elevated temperature environments. J. Agromet. **19**: 17.

Wu X., Tang Y., Li C. and Wu C. 2018. Characterization of the rate and duration of grain filling in wheat in southwestern China. Plant Prod. Sci., **21**(4): 358-369.

Würschum T., Langer S. M., Longin C. F. H., Tucker M. R. and Leiser W. L. 2017. A modern Green Revolution gene for reduced height in wheat. The Plant J., **92**: 892-903.

Yang C., Fraga H., van Ieperen W., Trindade H. and Santos J. A. 2019. Effects of climate change and adaptation options on winter wheat yield under rainfed Mediterranean conditions in southern Portugal. Climatic Change, **154**(1-2): 159-178.