

1 **Can crop phenology and plant height be channelized to improvise wheat productivity**
2 **in diverse production environments?**

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8

9 **Abstract**

10 Non-grain parameters like height, flowering and maturity should also be tried to break yield
11 plateau in wheat. This study explores such possibilities by analysing performance of released and
12 pre-released varieties evaluated in ten diverse production environments of India during the period
13 2000-2020. Regression analysis supports relevance of such non-grain determinants in grain yield
14 under every environment but magnitude of impact can vary. Collective contribution of non-grain
15 parameters can be high in a production environment where growth condition is most favourable
16 for wheat growth and every factor is important in such situations. They contribute less in the
17 environments engrossed with abiotic stress and merely one or two factors can be earmarked for
18 selection. Besides yield, this selection strategy can also enhance grain weight in certain
19 environments. At a time when selection for grain attributes is not providing further push; it would
20 be worth trying to explore these non-grain field indicators as selection strategy for further
21 advancement in productivity and grain weight of bread wheat.

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23

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

26

27 **Introduction**

28 Wheat (*Triticum aestivum* L.) is grown under diverse agro-ecological conditions across the globe. In
29 India also, it is cultivated under different production environments where growth conditions differ
30 and so is the yield harvest. It is obvious that besides productivity, field expression must also be
31 differing under diverse growth environment (Pandey *et al.*, 2015; Sharma *et al.*, 2019). Thus,
32 understanding of the changes occurring in the grain and non-grain yield parameters and the inter
33 trait relationship become important for the wheat breeders for further hike in yield potential. Plant
34 phenology which describes the timing of plant development has been acknowledged as a major
35 aspect of plant response to environment. Changing crop phenology can serve as important bio-
36 indicator in the era of climate change (Asseng *et al.*, 2017; Rezaei *et al.*, 2018). The adapted early
37 flowering cultivars successfully advance the onset of anthesis and the enforced longer grain filling
38 period reduces or avoids the risks of exposure to enhanced drought and heat stresses in late spring
39 (Solanki *et al.*, 2017; Yang *et al.*, 2019). Optimal height under given environmental condition is vital
40 for adaptability, productivity and yield stability of the wheat cultivars (Bognár *et al.*, 2007) whereas
41 maturity duration is the major genotypic cause of genotype-environment interaction (Garatuza-
42 Payan *et al.*, 2018; Singh *et al.*, 2017; Xie *et al.*, 2015).

43 Traditionally, grain number and grain weight have been recognized as main constituent of
44 wheat yield (Brinton and Uauy, 2019; Garatuza-Payan *et al.*, 2018) and wheat breeding programme
45 emphasise increase in the grain number through better tillering and spike characteristics. In some
46 wheat breeding centres of India, grain weight is also addressed in combination with the heat
47 tolerance programme (Braun *et al.*, 2010; Mishra *et al.*, 2014; Mondal *et al.*, 2016). Still, the yield
48 level keeps staggering and raising of the yield bar even by 5-10% turn out to be a difficult
49 proposition in certain regions. At this juncture, it is imperative to explore the role and contribution
50 of non-grain parameters (NGP's) namely plant height, maturity duration and heading days. It is a
51 general perception that adversary of climate change in wheat is first realised on NGP's and later

52 reflected in grain yield and size of the grain. Increased height and crop duration under favourable
53 growth condition often results in higher biomass production and accumulates more grain yield
54 (Reynolds *et al.*, 2009). Although NGP's are influenced by the abiotic factors; genetic constitution
55 also modulates their role in ascribing varietal differences. Therefore, it is crucial to understand
56 whether selection exercised on these field indicators can lead to yield improvement, if so up to
57 what extent and under which environment they can be exploited. Such studies attain more
58 prominence when production environments are highly diverse as observed in India. Few reports
59 from India have highlighted variations in the grain and non-grain attributes of wheat under diverse
60 growth environments (Mohan *et al.*, 2011; Mohan *et al.*, 2017). However, a comparative study to
61 demonstrate their contribution and potential role in yield enhancement without exerting any
62 undesired effect on grain size was lacking. Yield is expensive to pursue, therefore other objectives
63 must be attained before wide scale yield evaluation. Indian wheat programme provides perfect
64 platform for such investigations where high-yield genotypes of different genetic background are
65 being tested in several productions environments for a long time and data has been generated on
66 plant height, days to heading and maturity duration, grain yield and grain weight. Examining long-
67 term yield data of Indian wheat research programme, this study is an attempt to i) emulate
68 differential impact of NGP's and understand the interrelationship pattern, ii) realize their
69 comparative contribution in grain yield, iii) suggest ways to tap their potential for further increase
70 in wheat productivity and iv) search possibilities of simultaneous improvement in grain yield and
71 grain.

72

73 **Material and methods**

74 *Source of data*

75 The All India Coordinated Research Project on Wheat and Barley (AICRPW&B) conducts yield
76 evaluation trials to identify wheat genotypes suitable for a particular production environment. The

77 trials are conducted in two trial series i.e. timely-sown (TS) and late-sown (LS) in five wheat zones
78 of the country namely northern hills zone (NHZ), north-western plains zone (NWPZ), north-eastern
79 plains zone (NEPZ), central zone (CZ) and peninsular zone (PZ). This study analysed the data
80 generated by this national wheat research programme of India for the period 2000 to 2020.

81
82 arch ppexamined performance of the checks (released varieties) and the new test entries that
83 reached final year of testing (pre-released varieties) during the 20 year period 2000-19.

84
85 *Study material and production environments*

86 Study material involved released varieties (checks) and the pre-released high yielding wheat
87 varieties (entries in final year of testing) evaluated in advance varietal trials of AICRPW&B in ten
88 production environments i.e. two production conditions (TS and LS) and five zones. NHZ that
89 covers hills and foothills of the Himalayas has long winter with low temperature while NWPZ and
90 NEPZ represented the Indo-Gangetic plains (IGP). Study material involved released and pre-
91 released high yielding wheat varieties evaluated in two trial series of advance varietal trials
92 constituted by AICRPW&B in five diverse zones of the country i.e. NHZ, NWPZ, NEPZ, CZ and PZ.
93 NHZ that covers hills and foothills of the Himalayas has long winter with low temperature while
94 NWPZ and NEPZ represent the IGP. Among the five zones, NWPZ is the most productive wheat belt
95 of India. Climatic conditions in this zone are most ideal for wheat growth. In comparison, winter is
96 short and climate is normally humid in NEPZ. Wheat crop in CZ often face soil moisture stress and
97 high temperature as climate is hot and dry in this part of India. Peninsula in down south i.e. PZ has
98 similar temperature and soil but climate is not that dry. Planting of timely-sown wheat (TSW)
99 started with the onset of winter and was mostly completed by the end of October in the hills and by
100 the middle of November in the plains. The late-sown wheat (LSW) was planted 15-20 days after the
101 sowing schedule of TSW. Since LSW gets shorter life span therefore short duration genotypes fit in

102 this category. Fertilizer dose in TSW was 150N:60P:40K kg ha^{-1} in NWPZ/ NEPZ and 120N:60P:40K
103 kg ha^{-1} in the CZ/ PZ and NHZ whereas dosage in LSW was 90N:60P:40K kg ha^{-1} throughout the
104 country. No chemical was sprayed while raising the crop under these production environments.

105

106 *Variables and statistical analysis*

107 Since the trials involved multiple test sites, the zonal mean of each test entry was computed for
108 plant height (HT), days to maturity (DM), days to heading (DH), 1000 grain weight (TGW) and grain
109 yield. DH denoted the vegetative duration whereas difference between DM and DH represented the
110 grain filling duration (GFD) or the reproductive phase. Standardised data of each environment was
111 computed for regression analysis to assess relationship of NGP's in grain yield and grain weight.
112 Coefficient of determination (R^2) derived separately for individual or composite factors highlighted
113 comparative contribution of the NGP's individually and in combination. Pearson correlation
114 coefficient was calculated to understand association amongst the NGP's whereas coefficient of
115 variation (CV) was derived to estimate the level of diversity in different parameters. Difference
116 occurring in mean of two populations was compared by "t-test".

117

118 **Results and discussion**

119 *Diversity in production environments*

120 The ten production environments analysed in this study were quite diverse in expression of yield
121 and yield determining attributes (Table 1). Overall performance and the information provided on
122 field expressions during the 21 years revealed significant yield difference between two zones of IGP
123 i.e. NWPZ and NEPZ even when there was no difference in plant height. Difference in height was
124 conspicuous between NHZ and PZ under timely-sown condition as the NHZ crop was 15 cm taller
125 than PZ. NHZ also had 62 days maturity duration advantage in comparison to PZ but there was
126 hardly any difference in wheat productivity and TGW. Overall productivity was highest in NWPZ

127 and CZ and the yield levels also matched in both category of wheat i.e. TSW and LSW even though
 128 large maturity difference existed in both categories of wheat. Comparison of reproductive phase
 129 very clearly spelt that whatsoever be the difference in maturity duration; time taken to complete
 130 grain filling did not differ much. Under timely-sown condition, it was only CZ where grain maturity
 131 was completed in 50 days otherwise this process had taken 43-45 days in all other zones. Grain
 132 weight in TSW of CZ was exceptionally due to longer reproductive phase. In late-sown wheat,
 133 reduction in comparison to timely-sown material was obvious in all variables but zone-wise
 134 differentiation was same as observed in TSW. Mean yield of LSW was very low in NHZ mainly
 135 because HT was reduced drastically.

136 **Table 1.** Overall mean and coefficient of variation for six metric traits under diverse production
 137 environments of India

Characteristic	Timely-sown wheat					Late-sown wheat				
	NWPZ (123)	NEPZ (136)	CZ (58)	PZ (70)	NHZ (95)	NWPZ (121)	NEPZ (86)	CZ (89)	PZ (79)	NHZ (62)
Grain yield (g · m ²)	509	422	492	436	427	416	356	426	386	284
Heading days	96.8	79.3	67.7	61.2	126	82.6	67.7	62.2	56.4	105
Maturity days	142	122	117	106	169	121	107	106	97.2	145
Grain filling days	45.6	43.0	49.6	44.4	43.5	38.3	39.6	43.7	40.8	40.0
Plant height (cm)	93.8	91.6	88.7	82.4	98.7	88.2	85.7	80.2	79.3	82.5
1000-grain weight (g)	38.7	40.4	44.1	41.4	40.1	36.6	37.4	40.5	39.5	39.4
<i>Coefficient of variation (%)</i>										
Grain yield	10.2	08.9	08.4	09.8	15.1	09.8	09.0	09.9	09.1	19.8
Heading days	05.1	05.4	07.6	06.1	06.4	04.1	04.9	05.9	06.1	07.3
Maturity days	02.8	02.7	03.3	04.2	04.5	02.4	03.1	03.1	04.1	04.6
Grain filling days	07.3	06.5	06.5	06.3	15.8	07.5	07.5	06.1	08.8	15.3
Plant height	06.6	07.8	04.1	06.8	07.1	05.2	07.2	06.9	06.0	09.4
1000-grain weight	06.4	06.4	09.7	08.2	11.2	07.6	05.9	06.1	07.2	14.1

138 Figure in parenthesis indicate total number of entries evaluated during the 20-year study period

139

140 It was evident that wheat productivity did not commensurate with HT and DM in the same
141 manner under varying agro-climatic conditions. Unlike the plains, yield advantage due to HT or DM
142 was hard to realize in the hill region as cold stress might have restricted advantage of HT or DM in
143 TSW. Situation further aggravated in NHZ when there was ceiling on crop duration due to late
144 planting. This kind of abiotic stress led to reduction in HT; consequently, productivity in NHZ-LS
145 environment was lowest in the country. NWPZ and CZ were distinct from other zones in both
146 categories of wheat even though disparity persisted in DM and HT. Even with longer crop duration;
147 GFD in NWPZ was always shorter in comparison to CZ. As a result, improved grain weight
148 compensated the yield loss in CZ which the reduced grain number might have incurred because of
149 shorter vegetative period. Comparison of NWPZ and NEPZ revealed significant differences in
150 maturity and productivity even though there was no big difference in HT. It underlined that
151 association of the NGP's with wheat yield is based upon the growth conditions prevailing in that
152 particular environment. Influence of NGP's on wheat productivity cannot be adjudged from
153 differential wheat expression noticed under varying environments. It just helps to understand
154 characteristic features of wheat expression of different production environments.

155

156 *Divergence in NGP's interrelationship*

157 Understanding of relationship amongst the NGP's is crucial before analysing their impact on wheat
158 productivity. It was observed that besides overall expression, magnitude of variability also differed
159 in study material of each environment (Table 1). There were certain commonalities also in the
160 phenological expressions like CV derived for DM was always less in comparison to DH and GFD in
161 each environment and GFD expressed more variations in comparison to DH and DM in majority of
162 the cases. Maturity differences were lowest in the region where climate was most conducive for
163 wheat growth i.e. NWPZ. NHZ was distinct from the plains as variations in GFD, grain yield and
164 TGW were quite high. DM was less variable in NWPZ under both production conditions. HT

165 variations were highest in LSW of NHZ and lowest in TSW of CZ. It was an indication that
 166 relationship between the NGP's and their association with grain yield could differ in divergent
 167 production environments.

168 Relationship between the NGP's varied according to the variability noticed in the region.
 169 Correlation study revealed strong positive relationship between HT and DM in most of the cases
 170 except TSW of NHZ and LSW of NWPZ (Table 2). Although HT and DH are assumed to have strong
 171 positive relationship but this association was totally missing in NHZ. This relationship was also not
 172 visible LSW of NWPZ. It was obvious that variations in the pre-anthesis period had no significant
 173 impact on HT in such environments. DH was correlated positively with DM and negatively with GFD
 174 under all conditions but strong association between DM and GFD was not realised in TSW of NWPZ,
 175 NEPZ and CZ. It was an indication that variations occurring in DM might not have induced any shift
 176 in GFD in such environments. It was clearly evident that if certain associations which are so obvious
 177 otherwise (like relationship between HT and DM, DH and HT) fail to establish under certain
 178 environments in spite of comparable variation level (CV); it is fair enough to assume that the trend
 179 did not exist under those conditions. Every production environment has certain unique NGP
 180 relationships which account for differential impact on grain formation and grain development.

181 **Table 2.** Correlation coefficient between NGP's under different production environments

Relationship	Timely-sown wheat					Late-sown wheat				
	NWPZ	NEPZ	CZ	PZ	NHZ	NWPZ	NEPZ	CZ	PZ	NHZ
DM~HT	0.61**	0.30**	0.47**	0.34**	0.19	0.07	0.28**	0.45**	0.29*	0.37**
DM~DH	0.74**	0.76**	0.78**	0.78**	0.62**	0.59**	0.59**	0.71**	0.55**	0.63**
DM~GFD	0.09	0.01	-0.05	0.56**	0.39**	0.33*	0.45**	0.27*	0.59**	0.29*
DH~HT	0.56**	0.20*	0.58**	0.25*	0.12	0.10	0.27*	0.61**	0.25*	0.18
DH~GFD	-0.60**	-0.64**	-0.66**	-0.08	-0.48**	-0.57**	-0.46**	-0.49**	-0.35**	-0.57**

182 * and ** denote significance at $P \leq 0.05$ and 0.01 , respectively

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184

185

186 *NGP relationship with grain yield*

187 Phenology and plant height are major field expressions linked with wheat productivity in any
188 environment, representing manifestation of the genetic (vernalization, dwarfing and photoperiod
189 insensitive genes) and the non-genetic parameters like crop management and weather conditions
190 (Saiyed *et al.*, 2009; Yadav *et al.*, 2014). Similarly, maturity duration is slated to have strong positive
191 effect on the wheat yield (Garatuza-Payan *et al.*, 2018; Singh *et al.*, 2017; Xie *et al.*, 2015). Another
192 NGP associated with productivity variations is the plant height (Bognár *et al.*, 2007). Since HT is
193 also closely associated with DM, any alteration in height gets reflected in DM and the yield harvest.
194 It is quite obvious that wheat productivity differences under different environments occur mainly
195 because the duration to complete the life cycle differs. Due to diverse production environments and
196 genetic makeup of the test entries; difference in yield and maturity duration are quite large in the
197 Indian wheat. 21-year is a big time frame and so many variations must have occurred climatically
198 and different plant types must have been tested during this long spell in every production
199 environment. Fluctuations in weather conditions and diversity in the tested material therefore
200 must have recorded different levels of variations in the grain as well as non-grain attributes (Table
201 1).

202 It was amply clear that NGP's also play important role in regulating the yield potential as
203 each one expressed significant relationship in 7-8 out of 10 environments (Table 3). In view of
204 differential relationship amongst the NGPs, their contribution also varied under diverse production
205 environments. Regression analysis revealed that magnitude of association between NGP's and grain
206 yield varied in each environment. It was amply clear that NGP's also play important role in
207 regulating the yield potential as each one expressed significant relationship in 7-8 out of 10
208 environments. Amongst all environments, it was only TSW of NWPZ where every NGP established
209 significant relationship with grain yield. It simply means that when growth conditions are

210 favourable in a given environment, number of NGP's associated with yield also popup. There was no
 211 NGP which could establish relationship with yield under all conditions and the least important
 212 amongst them was GFD.

213 **Table 3.** Relationship of individual NGP with wheat yield in different production environments of
 214 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***	0.09***	0.14**	0.03	0.00	0.08**	0.04*	0.12***	0.10**	0.20***
DH	0.09**	0.01	0.10*	0.15***	0.04	0.03	0.10**	0.10**	0.16***	0.08*
GFD	0.09**	0.06**	-0.09*	0.00	0.01	0.07**	0.02	0.03	0.00	0.03
DM	0.39***	0.11***	0.03	0.12**	0.07**	0.22***	0.18***	0.23***	0.09**	0.03
HT+DH	0.46***	0.09**	0.16**	0.16**	0.04	0.11***	0.12**	0.13**	0.21***	0.25***
DH +GFD	0.45***	0.18***	0.12*	0.16**	0.07**	0.23***	0.19***	0.24***	0.16***	0.08
All NGP's	0.63***	0.22**	0.17**	0.16**	0.08*	0.30***	0.20***	0.27***	0.21***	0.27***

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

216

217 Although wheat productivity in NWPZ matched CZ under timely-sown condition, huge
 218 difference could be seen in the impact of NGP's. It underlined that the variations created in NGP's
 219 through scientific interventions and natural climatic variations were exploited to high capacity in
 220 TSW of NWPZ whereas prospects of exploiting such variations were rather limited in CZ (Table 1
 221 and 3). Relevance of individual NGP in yield of TSW in NWPZ was very high in case of HT and DM
 222 ($R^2: \geq 0.40$). Highest R^2 value recorded in TSW of all other zones was 0.15 noticed for DH in PZ. In
 223 LSW however, $R^2 \geq .20$ could be noticed for HT in NHZ and DM in NWPZ/ CZ.

224 Height and heading are two important growth factors related to the vegetative phase and it
 225 is important to understand and fragment their contribution during this developmental phase.
 226 Composite impact of these two factors was similar to that of HT in both production conditions of
 227 NWPZ, TSW of NEPZ/ CZ and LSW of NHZ (Table 3). It ascertained that during vegetative phase, it
 228 was only the height (not heading) which regulated wheat yield in such environments. It means that

229 when HT shows sign of increase due to favouring climate or the scientific interventions; no big yield
230 benefit is realised through DH in such environments which means that the grain number remains
231 nearly the same. Significant increase in grain number under such situations is feasible only when
232 tillering is enhanced through breeding. But when lateral growth intensifies, flowering is
233 automatically delayed and the prolonged vegetative phase results in increased grain number. At the
234 same time even if flowering gets extended due to agri-ecology or genotypic differences but crop
235 face abiotic pressure in the vegetative phase, there can always be reduction in plant height which
236 ultimately results in the yield loss (Anjum *et al.*, 2017). On the contrary, out of the two only DH
237 expressed significant contribution in TSW of PZ and LSW of NEPZ/ CZ which showed that benefit of
238 congenial climatic conditions in these environments was realised through DH only. Role of NGP's in
239 grain yield was limited in NHZ as only DM mattered to some extent in TSW whereas only HT was
240 prominent in LSW. Contribution of vegetative phase linked NGP's was significant in LSW of PZ
241 condition and synergy was derived when HT and DH were regressed together against yield.

242 Although several reports point relevance of GFD in grain development (Xie *et al.*, 2015; Wu
243 *et al.*, 2018), its positive contribution in yield could only be cited in some production environments
244 of northern plains of India, especially TSW of NWPZ and NEPZ; and LSW of NWPZ. Synergy was also
245 visible when DH and GFD were regressed together in both zones of IGP as DM turned highly
246 significant even though individual impact of HD or GFD was not high. Results related to CV had
247 illustrated that variation level recorded in DM was magnified in DH and GFD in many environments
248 and this distinction was very clear in northern India (Table 1). It underlines that increase in DH can
249 lead to better grain bearing in northern India but higher yield gain can only be achieved when
250 proper GFD is available. Similarly, enhanced GFD might fail to deliver good yield if flowering is
251 enforced early. Similar relationship could also be noticed in LSW of NEPZ and CZ. CZ was a unique
252 example where yield in TSW was benefitted by DH but impact of GFD was negative. As result, yield
253 registered no significant relationship with maturity in this particular environment. Increased TGW

254 in TSW of CZ was at the cost of reduced grain number affected by shortening of the vegetative
255 phase. This was the only production environment in the country where TGW was adversely related
256 to wheat productivity. Further, irrelevance of a given NGP in grain yield cannot be attributed to lack
257 of variability (Table 1); it can also happen when direct effect of a given component is marginal.

258

259 *Collective contribution of NGP's in grain yield*

260 In multiple regression analysis, R^2 value obtained through combinations like HT+DH+GFD,
261 HT+DH+MAT and all 4 NGP's together was similar. It's only because GFD was a derived component
262 from DM and DH. Since, it's not easy to exercise selection on the basis of GFD in the field, this factor
263 was excluded and the choice was limited to HT, DH and DM. Collective impact of NGP's was highly
264 significant in wheat yield of each production environment (Table 4). Indirect contribution of NGP's
265 was significant in every environment but the magnitude (R^2 value) varied from 0.07 to 0.61. In
266 comparison to individual effect, combination of NGP's was beneficial in majority of the cases. This
267 impact was highest in NWPZ in both categories of wheat and lowest in TSW of NHZ. R^2 value
268 underlines percent variations in yield associated with a given NGP or group of NGP's. In most
269 congenial wheat growing environment of the country i.e. TSW of NWPZ; even 61% yield variations
270 could be accounted by NGP's alone. In contrast, their contribution was limited to just 7%. Actually
271 level of cold stress vary each year in the hill due to climatic fluctuations which results into high
272 degree of yield fluctuations (Table 1). In all other production environments, 16 to 30% variations in
273 grain yield were accrued through NGP's. High R^2 value does not indicate that TSW of NWPZ could
274 make best use of the climatic conditions for suited for wheat growth. It could also have happened
275 because of the desired genetic variations created in NGP's through wheat breeding. Variations
276 derived through the scientific interventions can be spotted in the wheat genotypes developed in
277 this region for height and the phenological expressions. Emphasis in this region is also given to
278 effective tillering which influence height, heading and maturity as well. Plotting of grain yield

279 against maturity period countrywide (N: 919) had clearly illustrated that NWPZ-TS environment is
280 distinct, indeed as entries developed and tested in this environment (maturity: 142 ± 4 days)
281 formed a separate cluster altogether (Fig 1). Entries of the maturity range noticeable in NHZ (Table
282 1) were found scattered in another cluster. Irrespective of the production condition, all test entries
283 pertaining to the Indian plains (except NWPZ-TS), were accommodated in single cluster.

284

285 **Figure 1** Maturity duration and wheat productivity under Indian environments

286

287 *Key contributors in wheat yield*

288 Impact of individual components was also examined in the multiple regression analysis. It was
289 observed that all of them expressed significance only in TSW of IGP. Otherwise just one or two were
290 main drivers of this relationship. Analysis was further done to keep only those constituents which
291 exerted significance in multiple regression analysis (Table 4). Even though individual impact of
292 each constituent (HT, DH and DM) was positive in IGP (Table 3), contribution of DH turned negative
293 in this combined relationship. In NEPZ-TS environment, only HT and DM were relevant individually
294 (Table 3) but regression equation indicated that just like the adjoining zone i.e. NWPZ, DH was also
295 equally important and its indirect contribution was significant, too. Under late-sown condition, just
296 two factors i.e. HT and DM were found relevant in NWPZ whereas just one figured in NEPZ. In CZ,
297 only height mattered in TSW whereas maturity was crucial for LSW. Situation was different in the
298 adjoining PZ as only DH was the real deriving force in TSW whereas HT and DH were important in
299 LSW. In NHZ, DM proved to be the main yield regulator of TSW whereas HT was key yield
300 determinant in LSW. Importance of height in LSW of NHZ was also evident when zone-wise
301 comparison was made earlier in Table 1.

302

303 **Table 4.** Multiple regression statistics of key contributors in wheat yield in different production
304 environments

Parameter	Timely-sown wheat					Late- sown wheat				
	NWPZ	NEPZ	CZ	PZ	NHZ	NWPZ	NEPZ	CZ	PZ	NHZ
R ² : All NGP's	0.63***	0.22***	0.14**	0.16**	0.07*	0.28***	0.18***	0.23***	0.21***	0.20***
Coefficient of associated NGP										
Plant height	0.46***	0.11**	0.27**	NS	NS	0.23***	NS	NS	0.17*	0.33***
Heading days	-0.52***	-0.32**	NS	0.15***	NS	NS	NS	NS	0.34**	0.34**
Maturity days	0.86***	0.63***	NS	NS	0.23**	0.62***	0.42***	0.38**	NS	NS

305
306
307 *Selection strategy to harness yield and grain weight through NGP's*
308 Genetic variability, climatic variations and direct effect; they all matter in deciding the bottleneck
309 factor in grain yield under any production environment. It was quite evident in this study that
310 NGP's can be exploited as yield contributor in wheat. For effective implementation, it is imperative
311 to devise a strategy based upon minimum number of NGP's in such a way that there is simultaneous
312 gain in yield and TGW. If not, at least there should not be a case where yield gain is harnessed with a
313 premium on grain weight. Since all NGP's are not related to yield in every production environment
314 (Table 3), only the key components can be exploited to formulate selection index. Enrichment of
315 wheat yield through enhanced plant height and prolonged vegetative duration had been suggested
316 for the Indian subcontinent (Jamali and Ali, 2008; Laxman *et al.*, 2014). Reports from Pakistan and
317 China had also emphasised selection through improved height and larger flowering or reproductive
318 periods (Duan *et al.*, 2018; Khan *et al.*, 2000; Wu *et al.*, 2018). Advantage of height and crop
319 phenology had also been reported in some Indian environments by Mohan *et al.* (2017). Such
320 phenotypic expressions are indicators of good biomass accumulation accrued from healthier
321 vegetative growth. In the era of green revolution, reduced height had been preferred in wheat
322 breeding for a long time due to less lodging loss but it put a ceiling on the plant height, therefore,
323 the role of tall-dwarfs had also been acknowledged in the development of the high-yielding semi-

324 dwarf wheat's in the green revolution (Würschum *et al.*, 2017; Mohan *et al.*, 2017; Mohan *et al.*,
325 2017). It is also well established that flowering in wheat depends upon accumulation of certain
326 amount of heat units and this had been amply demonstrated earlier in two contrasting zones of
327 India i.e. NWPZ and CZ (Mohan *et al.*, 2017a). Thus breaking the yield barrier in wheat will require
328 fine tuning of the sink-source relationship which requires simultaneous increase in grain number
329 and the available assimilates for grain filling. But making selection for high tillering or grain bearing
330 is not easy. Often such plants flower late and get less time for proper grain filling.

331 On the basis of information gathered about the key components (Table 4), simple and easy
332 to adopt inference can be generated for simultaneous improvement in grain yield and grain weight.
333 Identification of key NGP's make the job easy for the breeders as by application of these 1-2
334 indicators in the field, significant yield improvement can be anticipated in wheat. The key factors
335 were common in TSW of NWPZ and NEPZ which underlines that positive selection for height and
336 maturity in early flowering genotypes can be highly useful to improve productivity of timely-sown
337 wheat in the IGP (Table 5). Besides yield, this selection strategy can also benefit TGW in a
338 significant way. To develop high yielding genotypes for LSW of NWPZ; field selection based upon
339 just two NGP's i.e. HT and DM can be instrumental for significant productivity improvement but
340 yield gain will be less in comparison to NWPZ and there shall not be any improvement in TGW
341 either. In LSW of NEPZ, only DM is the main predictor for yield and it also helps to improvise TGW
342 as well. Plant height should be given maximum importance in TSW of CZ whereas maturity is
343 crucial for LSW of the region. However, no extra advantage through TGW is expected through this
344 planning. Selection tool can be different in the adjoining PZ where DH is the lone predictor for grain
345 yield in TSW. When coupled with HT, significant yield gain can also be anticipated in LSW of the
346 region. Just like CZ, there is hardly any chance of grain size improvement through NGP's in PZ as
347 well. Since yield variations are usually high in NHZ, precision might lack in the estimated benefits of
348 NGP's. Still, selection for prolonged maturity in TSW and plant height in LSW can be expected to

349 boost wheat productivity. Preference to height in LSW of NHZ will also come in aid to grain weight
 350 of the harvested produce.

351 **Table 5.** NGP based selection criteria for simultaneous improvement in yield and grain weight of
 352 wheat

Zone	Selection criteria	Coefficient of determination (R ²)	
		Grain yield	Grain weight
<i>Timely-sown wheat</i>			
NWPZ-TS	Height, early flowering and maturity	0.631***	0.303***
NEPZ-TS	Height, early flowering and maturity	0.217***	0.130***
CZ-TS	Height, early flowering	0.141**	0.058
PZ-TS	Days to heading	0.154***	0.022
NHZ-TS	Early flowering, maturity	0.074*	0.004
<i>Late-sown wheat</i>			
NWPZ-LS	Height and maturity	0.283***	0.034
NEPZ-LS	Maturity	0.184***	0.178***
CZ-LS	Maturity	0.234***	0.005
PZ-LS	Height and days to heading	0.206***	0.065
NHZ-LS	Height	0.202***	0.121**

353
 354
 355 This study further adds that height accompanied with unstressed maturity duration ensures
 356 higher wheat productivity in most favourable wheat growth environment in India i.e. NWPZ-TS.
 357 Under late-sown condition, it is often difficult to pick genotypes which mature late as elevated
 358 temperature conditions and the hot winds enforce senescence in the leaves. Nevertheless, it is also
 359 well known that Sonalika, a prominent old cultivar for late-sown condition, had expressed
 360 productivity level well below the present varieties mainly because the new high-yield varieties
 361 have comparatively longer maturity duration. During last stage of this study period, all these
 362 components had been exploited in variety development programme of NWPZ-TS. Annual progress
 363 report of crop improvement (ICAR-IIWBR, 2019) had mentioned tremendous improvement in grain
 364 yield, plant height, bio-mass accumulation, harvest index, heading days and maturity duration when

365 growth condition were highly conducive. If performance of four leading TSW varieties of NWPZ (HD
366 2967, HD 3086, DBW 88 and WH 1105) common during the crop seasons 2018 to 2020 is
367 compared, average yield harvest was highest in 2019 (612 g m^{-2}) in comparison to the previous
368 year when yield was restricted to 539 g m^{-2} . It happened because there was 10 days increase in
369 maturity duration (from 141 to 151 days) and 6 cm increase in plant height (from 98 to 104 cm).
370 With increased height and favouring phenology, not only yield but TGW also increased from 38.8 to
371 40.3 g. In comparison to 2019 harvest season, wheat productivity in this region declined to 580 g m^{-2}
372 in 2020 as height was reduced by two cm and maturity period by three days. Comparison of
373 NGP's further revealed that genetic differences also counted for differential expressions in these
374 four high yielding varieties. HD 3086 excelled because of longer grain ripening period (49 days) and
375 good plant height (101 cm). HD 2967 drew advantage of extra height (103 cm) and longer maturity
376 duration (148 days). DBW 88 had plant height (102) and maturity duration (147 days) almost
377 similar to HD 2967 but it had advantage of early flowering and prolonged GFD. In spite of shorter
378 maturity period (145 days) and reduced plant height (99 cm), WH 1105 was high yielding because
379 phenology was partitioned well (HD: 98 days, GFD: 47 days).

380

381 **Conclusion**

382 Diverse production environments necessitate special wheat improvement strategy. At a time when
383 wheat is touching the yield plateau, it is pertinent that vista of non-grain plant attributes is also
384 reviewed. Breeders do keep an eye on these aspects while exercising selection in the segregating
385 material but which parameter is to be emphasized in a given environment is the key. Artificial
386 intelligence gathered through this investigation offers some silver lining. Simple and easily
387 adoptable selection methodology devised through this study will surely enhance the prospects of
388 yield improvement further. This information on potential uses of the non-grain yield determinants
389 can bridge some gap in the yield barrier realised not only in India but all over the world. It assures

390 that with some strategic planning; prospects of wheat productivity enhancement can be improvised
391 without directly touching the grain related parameters. Knowledge gained from this 21-years study
392 period assures that variability in NGP's exists in each production environment. In the past, this
393 variation was exploited to certain extent unknowingly. But when applied with some strategic
394 planning, prospects of yield improvement can surely be improved further. It's easy to make
395 selection for these phenotypic traits in the field as it will improvise biomass through plant height;
396 grain number through enhanced vegetative phase and grain weight by adjusting the grain filling
397 duration. Since impact can be different under divergent environments, breeders can choose the
398 factors or combination of NGP's required for yield improvement in a given environment.

399

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406

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Table 1. Overall mean and coefficient of variation for six metric traits under diverse production environments of India

Characteristic	Timely-sown wheat					Late-sown wheat				
	NWPZ (123)	NEPZ (136)	CZ (58)	PZ (70)	NHZ (95)	NWPZ (121)	NEPZ (86)	CZ (89)	PZ (79)	NHZ (62)
Grain yield (g · m ²)	509	422	492	436	427	416	356	426	386	284
Heading days	96.8	79.3	67.7	61.2	126	82.6	67.7	62.2	56.4	105
Maturity days	142	122	117	106	169	121	107	106	97.2	145
Grain filling days	45.6	43.0	49.6	44.4	43.5	38.3	39.6	43.7	40.8	40.0
Plant height (cm)	93.8	91.6	88.7	82.4	98.7	88.2	85.7	80.2	79.3	82.5
1000-grain weight (g)	38.7	40.4	44.1	41.4	40.1	36.6	37.4	40.5	39.5	39.4
<i>Coefficient of variation (%)</i>										
Grain yield	10.2	08.9	08.4	09.8	15.1	09.8	09.0	09.9	09.1	19.8
Heading days	05.1	05.4	07.6	06.1	06.4	04.1	04.9	05.9	06.1	07.3
Maturity days	02.8	02.7	03.3	04.2	04.5	02.4	03.1	03.1	04.1	04.6
Grain filling days	07.3	06.5	06.5	06.3	15.8	07.5	07.5	06.1	08.8	15.3
Plant height	06.6	07.8	04.1	06.8	07.1	05.2	07.2	06.9	06.0	09.4
1000-grain weight	06.4	06.4	09.7	08.2	11.2	07.6	05.9	06.1	07.2	14.1

Figure in parenthesis indicate total number of entries evaluated during the 20-year study period

Table 2. Correlation coefficient between NGP's under different production environments

Relationship	Timely-sown wheat					Late-sown wheat				
	NWPZ	NEPZ	CZ	PZ	NHZ	NWPZ	NEPZ	CZ	PZ	NHZ
DM~HT	0.61**	0.30**	0.47**	0.34**	0.19	0.07	0.28**	0.45**	0.29*	0.37**
DM~DH	0.74**	0.76**	0.78**	0.78**	0.62**	0.59**	0.59**	0.71**	0.55**	0.63**
DM~GFD	0.09	0.01	-0.05	0.56**	0.39**	0.33*	0.45**	0.27*	0.59**	0.29*
DH~HT	0.56**	0.20*	0.58**	0.25*	0.12	0.10	0.27*	0.61**	0.25*	0.18
DH~GFD	-0.60**	-0.64**	-0.66**	-0.08	-0.48**	-0.57**	-0.46**	-0.49**	-0.35**	-0.57**

* and ** denote significance at $P \leq 0.05$ and 0.01 , respectively

Table 3. 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***	0.09***	0.14**	0.03	0.00	0.08**	0.04*	0.12***	0.10**	0.20***
DH	0.09**	0.01	0.10*	0.15***	0.04	0.03	0.10**	0.10**	0.16***	0.08*
GFD	0.09**	0.06**	-0.09*	0.00	0.01	0.07**	0.02	0.03	0.00	0.03
DM	0.39***	0.11***	0.03	0.12**	0.07**	0.22***	0.18***	0.23***	0.09**	0.03
HT+DH	0.46***	0.09**	0.16**	0.16**	0.04	0.11***	0.12**	0.13**	0.21***	0.25***
DH +GFD	0.45***	0.18***	0.12*	0.16**	0.07**	0.23***	0.19***	0.24***	0.16***	0.08
All NGP's	0.63***	0.22**	0.17**	0.16**	0.08*	0.30***	0.20***	0.27***	0.21***	0.27***

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

Table 4. Multiple regression statistics of key contributors in wheat yield in different production environments

Parameter	Timely-sown wheat					Late- sown wheat				
	NWPZ	NEPZ	CZ	PZ	NHZ	NWPZ	NEPZ	CZ	PZ	NHZ
R^2 : All NGP's	0.63***	0.22***	0.14**	0.16**	0.07*	0.28***	0.18***	0.23***	0.21***	0.20***
Coefficient of associated NGP										
Plant height	0.46***	0.11**	0.27**	NS	NS	0.23***	NS	NS	0.17*	0.33***
Heading days	-0.52***	-0.32**	NS	0.15***	NS	NS	NS	NS	0.34**	0.34**
Maturity days	0.86***	0.63***	NS	NS	0.23**	0.62***	0.42***	0.38**	NS	NS

Table 5. NGP based selection criteria for simultaneous improvement in yield and grain weight of wheat

Zone	Selection criteria	Coefficient of determination (R^2)	
		Grain yield	Grain weight
<i>Timely-sown wheat</i>			
NWPZ-TS	Height, early flowering and maturity	0.631***	0.303***
NEPZ-TS	Height, early flowering and maturity	0.217***	0.130***
CZ-TS	Height, early flowering	0.141**	0.058
PZ-TS	Days to heading	0.154***	0.022
NHZ-TS	Early flowering, maturity	0.074 [†]	0.004
<i>Late-sown wheat</i>			
NWPZ-LS	Height and maturity	0.283***	0.034
NEPZ-LS	Maturity	0.184***	0.178***
CZ-LS	Maturity	0.234***	0.005
PZ-LS	Height and days to heading	0.206***	0.065
NHZ-LS	Height	0.202***	0.121**

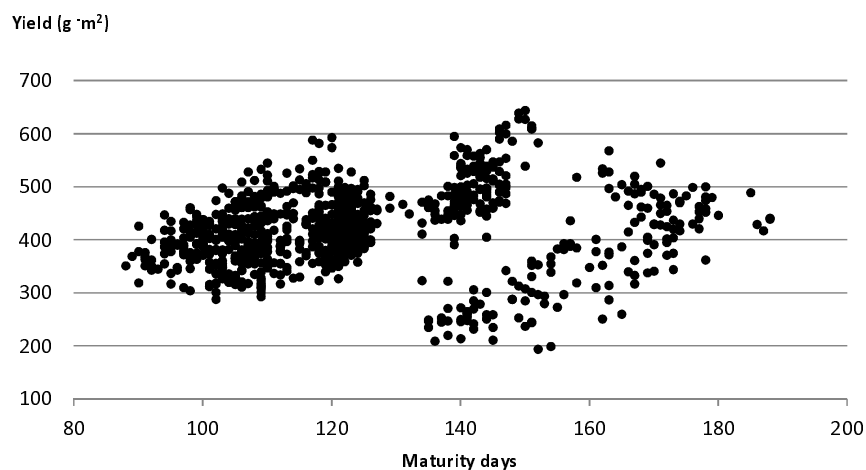


Figure 1 Maturity duration and wheat productivity under Indian environments