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Effects of Pedoclimate and Agronomical Management on Yield and Quality of Common Wheat Varieties (*Triticum aestivum* L.) in Afghanistan

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Abstract: The lower common wheat productivity and quality are major constraints in Afghanistan. The objectives of this study were to (1) quantify the effect of soil and climatic parameters on the yield and quality of common wheat and (2) investigate the response of different wheat varieties to different N and P fertilization rates, to improve the yield and quality of common wheat. Three wheat varieties (DLN7, ZRDN, and KBL13), three phosphorus levels (PL) at 60, 90, and 120 kg P_2O_5 ha^{-1}, and three nitrogen ratios (NP) at 1:1, 1.25:1, and 1.5:1, respectively, in four locations (L), were evaluated. The higher average grain yield (GY), straw yield (SY), and starch yield (STY) were obtained with DLN7, followed by KBL13 and ZRDN, for all locations. As PL increased, GY, SY, protein yield (PY), and STY significantly increased in all locations. The PL significantly affected protein content (PC), gluten content (GC), and dough strength (W). The NP significantly improved PC, GC, and PY. Starch (ST), STY, and amylopectin (AP) increased significantly with increasing PL. The amylose to AP ratio increased significantly with increasing NP ratios. The findings show that at NP1/PL120, GY, SY, ST, and AP improved significantly, while at NP1.5:1/PL120, PC and GC improved significantly.

Keywords: phosphorous fertilization; nitrogen to phosphorous ratio; gluten; amylopectin; amylose to amylopectin ratio; soil-available phosphorous; starch

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1. Introduction

Agriculture is the backbone of the Afghan economy, accounting for approximately one-quarter of the national GDP, and it is among the major sectors [1]. About 80% of the Afghan population is directly or indirectly involved in the agriculture sector [2]. However, the growth of agriculture has been highlighted as an essential factor in driving the country's economy and improving people's livelihood and national food security [3]. Common wheat is the most dominant agricultural crop in Afghanistan, followed by horticultural crops (fruits, nuts, and vegetables) and intensive livestock production (milk, eggs, and poultry meat). Therefore, wheat alone accounts for one-quarter of agriculture GDP and 6.3% of the national GDP [1]. Common wheat grows all over the country, and it accounts for 82% of total cereal consumption [4]. Despite common wheat being the principal agricultural crop in Afghanistan, domestic production fails to meet the national demand. About 2 million tons of wheat are imported annually to fulfil the national demand (7 million). As a result, Afghanistan is ranked as one of the world's top importing countries [5]. Additionally, the quality of local wheat production is quite poor compared to the imported grain [5]. The average wheat productivity per unit area is estimated to be very low (2.6 and 1 t ha^{-1} in irrigated and rainfed conditions, respectively) compared to India's 3.5 t ha^{-1} [6]. However, variable limiting factors in response to wheat productivity and quality in Afghanistan are reported. For example, MAIL (2013) [7] reported that the lack of farmer awareness regarding the use of appropriate agronomic practices and the shortage of water were among the major challenges. Elrashidi et al. (2012) [8] indicated that higher pH values and $CaCO_3$ concentrations in the soil, along with lower available phosphorus and organic matter, contribute to lower wheat production in Afghanistan. Additionally, Sharma and Nang (2018) [9] highlighted that drought, pests, diseases, and insufficient seed quality are known to hamper wheat productivity and quality in Afghanistan. Likewise, Kazimi (2018) [10] reported that the inadequate use of organic residues, poor attention to crop rotation, and heavy tillage have been identified as limiting factors for yields and soil degradation in Afghanistan.

Researchers must focus on the yield gap and determine the difference between actual farm productivity (quantitatively and qualitatively) and what is hypothetically achievable under ideal management [6]. Additionally, ARIA (2022) [11] reported that there is big potential to increase wheat productivity in Afghanistan. The research results showed that the application of improved agronomic practices (appropriate fertilization schemes, optimal sowing time, effective irrigation, and efficient weed and pest control) would increase wheat productivity and grain quality in Afghanistan [12].

Producing optimal quality wheat plays a more substantial role in human nutrition. Grain quality depends on two main components, namely starch and protein contents. In particular, wheat grain is composed of 60 to 70% starch, 8 to 18% protein, 1 to 2% lipids, and 3 to 4% minerals [13]. However, it is well known that the components of stored wheat starch and proteins can be greatly improved through genetic and fertilization strategies, which together determine the final quality of the wheat grain [14]. Research proposes that proper N (nitrogen) fertilization could significantly improve wheat grain protein and gluten concentration [15]. Since the ratio between glutenin and gliadin can determine dough's rheological characteristics, a study reported that under low N and P (phosphorus) treatments, the grain gliadin content significantly improved, while a significant reduction was observed in the glutenin fractions [16]. Phosphorus fertilization is an important factor that can significantly influence grain development and improve starch content and its molecular components [17]. Besides the environment, P fertilization also plays a key role in achieving higher grain yield and enhancing starch and protein concentration in wheat [18]. Proper N fertilization can greatly influence seed storage protein accumulation, grain processing, desirable baking value, and the overall healthiness of the final end-use products [19].

Despite the extensive research carried out in the past to assess the effect of N on wheat quality, there is still limited information available on the grain protein sub-fraction and starch content [20]. Similarly, insufficient studies have been conducted on starch granule distribution and its content in wheat grain [17]. Both N and P fertilizers are essential nutrients for normal growth, wheat quality, and productivity, and their balanced application is crucial [16]. Therefore, the objectives of this study were to (1) quantify the effect of soil and climatic parameters on wheat yield and quality and (2) investigate the response of different wheat varieties to various N and P fertilization rates under specific climate conditions, aiming to improve the yield and quality of wheat in Afghanistan.

2. Materials and Methods

2.1. Experimental Fields' Set-Up

The research was performed over two growing seasons (GS), from September 2020 to July 2022, in four locations (L), each in different agro-climatic zones (ACZ) of Afghanistan: Baghlan (BGL) in the North-East (ACZ-NE), Balkh (BLK) in the North (ACZ-N), Helmand (HLM) in the South-West (ACZ-SW), and Herat (HRT) in the West (ACZ-W) (Figure 1).

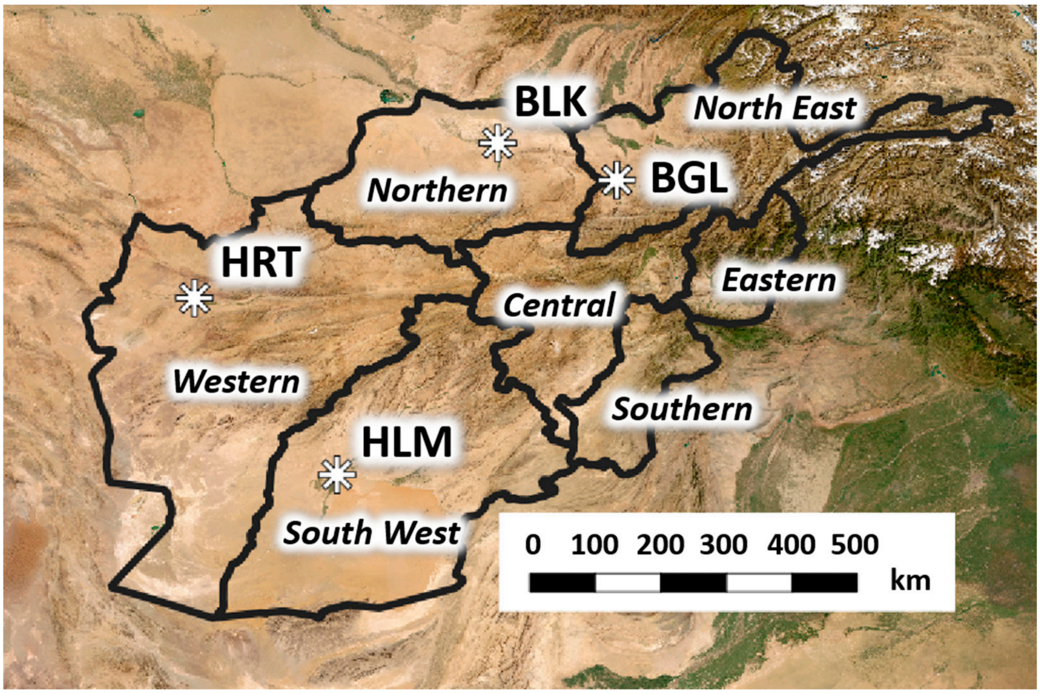

Figure 1. A map of Afghanistan displaying the four locations (white stars) where experimental camps were established: Baghlan (BGL), Balkh (BLK), Helmand (HLM), and Herat (HRT). The agro-climatic zones of Afghanistan are also reported.

BGL, BLK, and HRT experienced a semi-arid climate, while HLM had an arid climate. Daily precipitation and daily average temperature (Tavg; °C) data from the NASA database (https://power.larc.nasa.gov/data-access-viewer/, accessed on 2 March 2023) were used to calculate the average precipitation and temperature on a monthly basis for a long-term period (2001–2020) as well as for the 1st and 2nd GS. For each location and growing season (GS), the cumulative precipitation values from tillering to the grain filling period (P_TGf) were calculated as reported in [21]. Growing degree day (GDD) data [22] were used to describe the timing of biological processes [23,24]. According to Fabbri et al. (2020) [24], the daily GDD value was set to 0 °C for Tavg at or below 4 °C, whereas for Tavg higher than 4 °C, it was calculated as the difference between Tavg and 4 °C. Then, the daily GDD values were cumulated for the period from tillering to grain filling (GDD_TGf). In all locations, soils were alkaline with a low concentration of organic matter (OM; %), available P (Av_P; mg P kg^{-1}), and total N (Tot_N; %), while they had a sufficient amount of available potassium (Av_K; mg K kg^{-1}) (Table 1). Among the four locations, the BGL soil was the richest in nutrients, especially available P and total N, while the HRT soil was the poorest.

Table 1. The soil properties of different locations.

Location	pH	OM (%)	Av_P (mg P kg^{-1})	Av_K (mg K kg^{-1})	Tot_N (%)	Soil Texture
BGL	7.9	1.58	7.2	135	0.16	Silty loam
BLK	8.3	1.15	6.2	120	0.12	Silty loam
HLM	8.2	1.31	5.6	132	0.11	Silty loam
HRT	8.4	0.86	4.5	118	0.05	Sandy loam

A plot experiment with plot dimensions of 2.5 × 2 m, covering a surface area of 5 m^2, was arranged in a factorial randomized complete block design (FRBD). A total of twenty-seven treatments, with three replicates, were obtained from the factorial combination of 3 phosphorus levels (PL) (60, 90, and 120 kg P_2O_5 ha^{-1}, namely PL60, PL90, and PL120, respectively), 3 nitrogen to phosphorous (NP) rates (1:1, 1.25:1, and 1.5:1; namely NP1, NP1.25, and NP1.5) (Table 2), and 3 common wheat (*Triticum aestivum* L.) varieties (Gen): Darulaman07 (DLN7), Kabul-13 (KBL13), and Zardana-89 (ZDNA).

Table 2. P and N rates for each combination of PL and NP treatments.

Treatments		**P Rate (kg P_2O_5 ha^{-1})**	**N Rate (kg N ha^{-1})**
PL	**NP**		
PL60	NP1	60	60
	NP1.25		75
	NP1.5		90
PL90	NP1	90	90
	NP1.25		113
	NP1.5		135
PL120	NP1	120	120
	NP1.25		150
	NP1.5		180

Both DLN7 and KBL13 were improved varieties created by breeding by the International Maize and Wheat Improvement Center (CIMMYT), while ZDNA was an improved variety from Pakistan. The pedigree of DLN7, KBL13, and ZDNA were WEAVER/4/NAC/TH.AC//3*PVN/3/MIRLO/BUCCID/SID:133428/10, WAXWING*2/TUKURU, and CNO67/8156//TOB66/CNO67/4/NO/3/12300//LR64A/8156/5/PVN, respectively. The DLN7 is an improved wheat variety characterized by good resistance to yellow rust and a grain yield (GY) potential of 4 t ha^{-1} [25]. The KBL13 is considered the most promising variety for improving Afghan wheat production in the coming time due to its resistance to Ug99 and other rust varieties, as well as its capability of producing an average GY of over 4.4 t ha^{-1} [21]. Since the mid-1990s, ZDNA has been one of the most popular varieties of common wheat in the northern regions of Afghanistan, given the higher average yields than other local varieties [26,27]. Because of its diffusion among farmers, ZDNA is generally used as a benchmark variety in Afghanistan [28].

The soil was plowed at a depth of 0.40 m and then harrowed at a depth of 0.10 m in October for two consecutive growing seasons (2020/2021 and 2021/2022, namely 1st GS and 2nd GS). The forecrop was common wheat in all locations and both GS. Sowing was performed by distributing 120 kg of seed ha^{-1} (about 300 seed m^{-2}) with a row spacing of 0.2 m (10 rows per plot). Within each plot, the six central rows (cut off 0.5 m at both ends) were used for sampling and data collection (a sampling area of 1.8 m^2). Although no phytosanitary products for plant protection were used, the plants were observed to be healthy with no damage. All of the phosphorus (P) was distributed in the form of di-ammonium phosphate (DAP, P_2O_5: 46%) just before sowing. The nitrogen (N) amount to be distributed in each plot was calculated taking into account the PL and the established NP ratio. The total N to be distributed in each plot was reduced by the amount of N in DAP, while the remaining N in the form of urea (N: 46%) was applied 50% at tillering and 50% at stem elongation. In all the experimental fields, furrow irrigation with riverine water was carried out to satisfy the crop's water requirements during the common wheat growing season, following the protocol reported in [21]. All field activities were manually performed (i.e., sowing, fertilizer distribution, weeding, irrigation, harvesting, and threshing). For each plot, the grain yield (GY, adjusted to 12% of moisture), the straw yield (SY; kg ha^{-1}), and the thousand kernel weight (TKW; g 1000 $seeds^{-1}$) were measured at harvesting.

2.2. Analysis of Kernel and Dough

Wholemeal flour samples were obtained for each treatment using a grinder with a 0.5 mm screen (Cytolec 1093 lab mill, FOSS Tecator, Hoganas, Sweden) [21,29]. A CHNS analyzer (CHN-S Flash E1112, Thermo-Finnigan LLC, San Jose, CA, USA) was used to determine the total N percentage in wholemeal flour samples (5 mg per sample). The N percentage was then converted to total protein content in wholemeal (PC; %) by multiplying by 5.7, following ICC Standard 167 (2000). The gluten content in wholegrain flour (GC; %) was determined as reported in [29,30]. The starch content in wholegrain flour (ST; %) was determined using a Total Starch Assay Kit (K-TSTA, Megazyme, Irishtown, Ireland) as reported in [31]. The amylose (AM; %) and amylopectin (AP; %) percentages in ST were determined using a Megazyme Amylose/Amylopectin Assay Kit (Megazyme Ltd., Bray, Ireland) following the procedures indicated by the manufacturer [32]. Accordingly, the AM to AP ratio (AM:AP) was calculated. Dough strength (W; 10^{-4} J) was tested according to ISO 27,971 (2015), as reported in [30]. The protein and starch yield per hectare (PY and STY; kg ha^{-1}) were calculated as the product of grain yield using protein concentration and starch concentration, respectively.

2.3. Statistical Analysis

A multifactorial analysis of variance (ANOVA) was performed to determine the main effect of PL and NP treatments and their interactions, utilizing RStudio (R 4.1.1). In the case of significant differences, the Tukey HSD post hoc test was used to compare the differences between means. Significance was indicated as follows: * = 0.05, ** = 0.01, *** = 0.001, and n.s. for not significant. To assess the relative influence of explanatory variables on the variation of winter wheat agronomic traits (GY, PC, GC, ST, and W), a gradient-boosted regression tree (GBRT) statistical analysis was performed. A correlation matrix was employed to eliminate collinear variables and to check for redundancy among covariates, using a threshold of 0.8. The fit of the GBRT model was analyzed using a ten-fold cross-validation and was performed with a tree complexity of 5 and a learning rate of 0.01.

3. Results

3.1. Meteorology Data

During the 1st GS, the average temperature pattern from September to December was slightly lower compared to the long-term data for all locations (Figure 2). Regarding precipitation, in the 1st GS, the average precipitation amount was lower for all locations with respect to the long-term data. However, exceptionally, only in November, the precipitation was higher for all locations compared to the long-term data. For the 2nd GS, the monthly average temperature data were similar to long-term data at BGL, BLK, and HRT, but in HLM, the monthly average temperature data were slightly lower than the long-term values. The precipitation amount was higher in the 2nd GS for all locations compared to the long-term data and the 1st GS. Therefore, the months of January, March, and May received higher precipitation at BGL, HRT, and BLK, respectively, compared to the long-term. However, in HLM, higher precipitation was recorded in January and July compared to the long-term data and the other locations. On average, BGL was the wettest among all locations, followed by HRT in the 2nd GS, compared to BLK and HLM.

3.2. Agronomic Parameters

The L was the dominant factor for grain yield and straw yield, followed by PL, GS, and Gen (Table 3). Further, NP significantly affects grain yield, but not straw yield. Additionally, grain yield was significantly affected, in decreasing order, by the following first-order interactions: L×PL, GS×L, PL×NP, GS×Gen, GS×NP, and L×Gen. On the other hand, straw yield was significantly affected, in decreasing order, by the following first-order interactions: GS×L, PL×NP, L×PL, L×Gen, and L×NP.

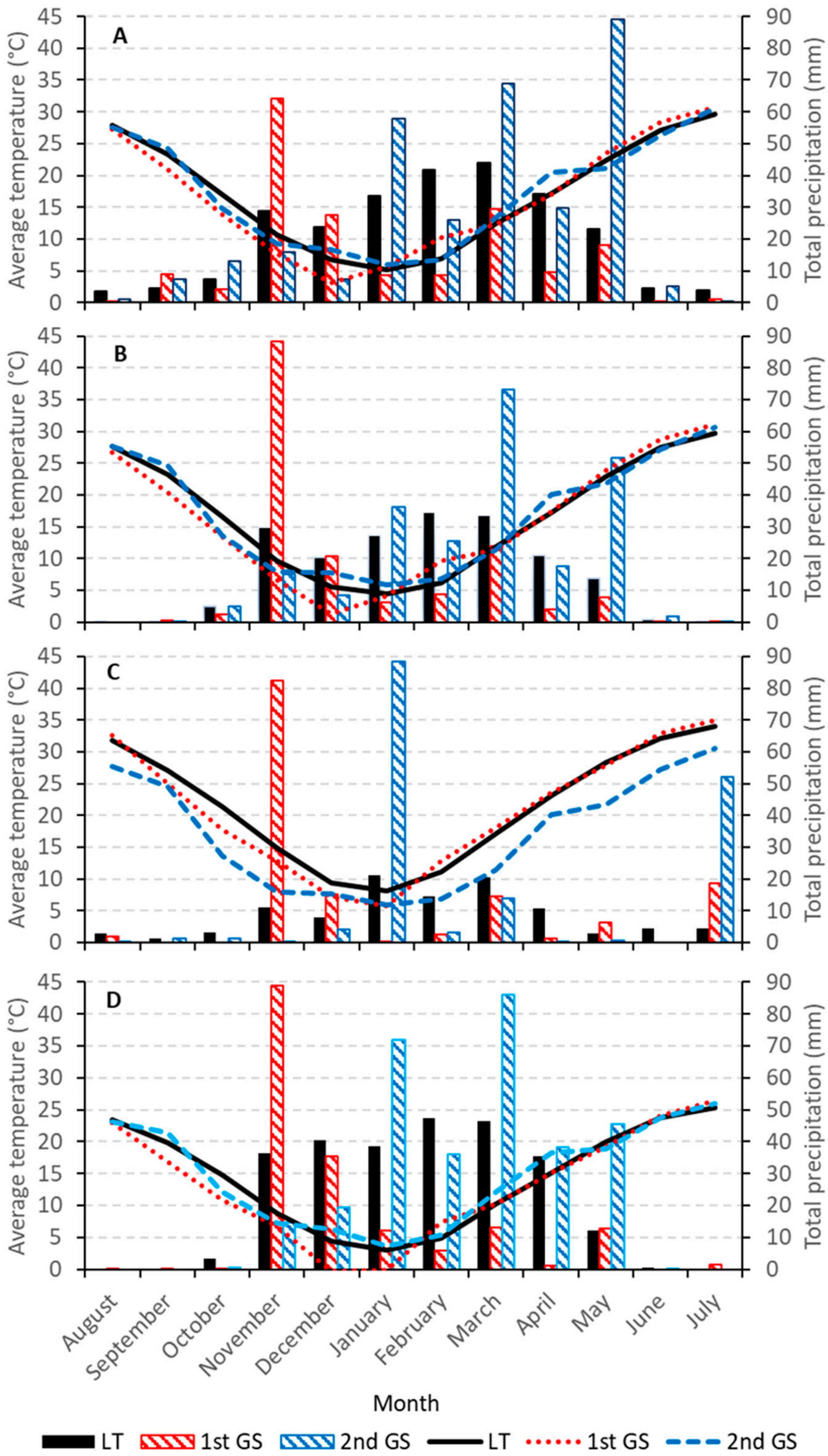

Figure 2. Walter–Lieth diagram of the study sites. (**A**) Baghlan (BGL), (**B**) Balkh (BLK), (**C**) Helmand (HLM), and (**D**) Herat (HRT). The histograms represent the monthly average precipitation (mm), while the lines represent the average monthly temperature (°C). The values were calculated for the following periods: the long-term (LT) span (2001–2020), the first growing season (1st GS) (2020/2021), and the second growing season (2nd GS) (2021/2022).

Table 3. Results of the ANOVA on grain yield (GY), straw yield (SY), and thousand kernel weights (TKWs) in relation to variation sources: growing season (GS), location (L), variety (Gen), phosphorous fertilization level (PL), nitrogen to phosphorous ratios (NP), and their interactions. The table columns report the Fisher F (F) and the significance levels: * = 0.05, ** = 0.01, *** = 0.001, ns = not significant.

Variation Source	DF	GY ($t\ ha^{-1}$)		SY ($t\ ha^{-1}$)		TKW (g)	
		F	sig	F	sig	F	sig
GS	1	243.1	***	94.5	***	136.8	***
L	3	995.1	***	613.2	***	149.6	***
Gen	2	77.3	***	44.1	***	8.3	***
PL	2	293.3	***	156.9	***	0.2	ns
NP	2	8.2	***	5.9	**	0	ns
GS×Gen	2	8.1	***	1.1	ns	0.8	ns
GS×L	3	21.3	***	37.6	***	125.5	***
GS×NP	2	6	**	0.2	ns	0.2	ns
GS×PL	2	2.2	ns	2.5	ns	3.4	*
L×Gen	6	5.8	***	10.2	***	7.6	***
L×NP	6	1.6	ns	5.7	***	0.3	ns
L×PL	6	25.1	***	10.8	***	1.4	ns
Gen×NP	4	0.4	ns	1	ns	1.3	ns
Gen×PL	4	2.6	*	0.2	ns	0.8	ns
PL×NP	4	15.8	***	13.4	***	2.5	*
Residuals	432						

The highest average grain yield and straw yield values were detected in DLN7, followed in decreasing order by KBL13 and ZRDN (Table 4). The average grain yield and straw yield measured in DLN7 were significantly different from those measured in ZDNA, while no significant difference was detected between KBL13 and the other two varieties. As the PL increased, both grain yield and straw yield significantly increased, with an increment of 29.43% and 26.44%, respectively, from PL60 to PL120. The average grain yield and straw yield values measured at BGL were significantly higher than those measured in the other locations, while the lowest average grain yield and straw yield values were measured at HRT.

In BGL, BLK, and HRT, grain yield increased significantly as PL increased from 60 to 120 kg P_2O_5 ha^{-1}. Instead, in HLM, grain yield significantly increased as PL increased from 90 to 120 kg P_2O_5 ha^{-1}, while no significant difference in grain yield was detected between the PL60 and PL90 levels. Likewise, in BGL and HRT, straw yield increased significantly as PL increased from the first to the third PL level, while in BLK and HLM, significant straw yield increases were detected only between the second and the third PL level. Considering the interaction between PL and the NP ratio, grain yield significantly increased as the NP ratio increased ($p < 0.05$) at PL60, increasing by about 15% from NP1 to NP1.5. Instead, grain yield was not significantly affected by NP at PL90, while it was negatively affected ($p < 0.05$) at PL120, decreasing grain yield by about 5.4% from NP1 to NP1.5. Straw yield significantly increased as the NP ratio increased from 1 to 1.25 ($p < 0.05$) by about 18.3% at PL60. Also, the NP ratio did not significantly affect straw yield at PL90, while it negatively affected straw yield ($p < 0.05$) at PL120, decreasing straw yield by about 3.1% as the NP ratio increased from 1 to 1.5. The highest grain yield and straw yield production were obtained at PL120 and NP1. In all locations, DLN produced significantly more grain yield than ZDNA. In BGL, the grain yield of the KBL13 variety was not significantly different from that of DLN7 but significantly more than the grain yield of ZDNA. In HLM, the grain yield of the KBL13 variety was not significantly different from that of ZDNA and significantly less than the grain yield of DLN7. Furthermore, the grain yield produced by KBL13 was not significantly different from DLN7 and ZDNA in BLK and HRT.

Table 4. The mean grain yield (GY), straw yield (SY), and thousand kernel weights (TKWs) due to the main effect of the growing season (GS), location (L), nitrogen to phosphorous ratios (NP), phosphorus (PL) fertilization, and varieties (Gen). The table columns report the ANOVA result as * = 0.05, ** = 0.01, *** = 0.001, and ns = not significant, whereas the lowercase letters show the Tukey HSD post hoc test results, and the value inside parentheses represents standard error.

Treatments	GY ($t\ ha^{-1}$)		SY ($t\ ha^{-1}$)		TKW (g)	
	Average	sig	Average	sig	Average	sig
Gen		***		***		***
DLN7	5.26 (0.42)	a	9.12 (0.74)	a	39.81 (0.61)	a
KBL13	5.01 (0.39)	ab	8.64 (0.73)	ab	38.66 (0.57)	b
ZDNA	4.62 (0.37)	b	8.05 (0.61)	b	38.75 (0.71)	b
PL ($kg\ ha^{-1}$)		***		***		ns
PL60	4.28 (0.3)	c	7.6 (0.59)	c	38.97 (1.48)	
PL90	5.07 (0.41)	b	8.61 (0.65)	b	39.15 (1.27)	
PL120	5.54 (0.41)	a	9.61 (0.76)	a	39.1 (1.34)	
NP		ns		ns		ns
NP1:1	4.91 (0.42)		8.4 (0.70)		39.12 (1.49)	
NP1.25:1	4.89 (0.37)		8.63 (0.67)		39.03 (1.33)	
NP1.5:1	5.08 (0.39)		8.78 (0.74)		39.07 (1.28)	
L		***		***		***
BGL	6.89 (0.36)	a	11 (0.73)	a	37.3 (1.11)	b
BLK	4.59 (0.19)	b	7.25 (0.39)	c	41.67 (2.03)	a
HLM	4.65 (0.28)	b	10.04 (0.68)	b	41.75 (0.95)	a
HRT	3.73 (0.25)	c	6.13 (0.51)	d	35.58 (2.03)	c
GS		***		***		***
1st GS	4.63 (0.35)	b	8.15 (0.62)	b	37.58 (1.51)	b
2nd GS	5.30 (0.35)	a	9.06 (0.63)	a	40.57 (0.72)	a

In the present study, L was the dominant factor for TKW, followed by GS and Gen, while PL and NP did not significantly affect TKW. Additionally, TKW was significantly affected by first-order interactions GS×L, L×Gen, GS×PL, and PL×NP, while the other first-order interactions were not found to be statistically significant for TKW. The average TKW value measured in DLN7 was significantly higher than the values measured in KBL13 and ZDNA, while no significant differences were detected between KBL13 and ZDNA. The average TKW values measured in HLM and BLK, which showed no significant differences, were significantly higher than the values measured in BGL and HRT. Meanwhile, the lowest average TKW value was measured in HRT.

3.3. Protein, Starch, and Alveograph Parameters

The Gen was the dominant factor for protein concentration, followed by L, NP, PL, and finally GS (Table 5). Additionally, protein concentration was significantly influenced in decreasing order by the following first-order interactions: Gen×NP, PL×NP, L×Gen, Gen×PL, and GS×L. The highest average protein concentration and gluten concentration values were determined in ZRDA, while the lowest values were determined in KBL13 (Table 6). The average protein concentration significantly increased by 1.7% from PL60 to PL120. However, protein concentration increased by 2.72% from NP1 to NP1.25, but a further increase in NP did not significantly affect protein concentration. The highest average protein concentration was determined in HRT, followed by HLM, while the lowest protein concentration was measured at BGL. BLK and HLM showed similar protein concentration values.

Table 5. Results of the ANOVA on protein concentration (PC), protein yield (PY), gluten concentration (GC), dough strength (W), starch content (ST), starch yield (STY), amylopectin concentration (AP), and amylose to amylopectin ratio (AM:AP). The main effect of the growing season (GS), location (L), nitrogen to phosphorous ratios (NP), phosphorus (PL) fertilization, and varieties (Gen), and their first-order interactions, are reported.

Variable Source	DF	PC (%)		PY (kg ha^{-1})		GC (%)		W (10^{-4} J)		ST (%)		STY (t ha^{-1})		AP (%)		AM:AP (%)	
		F	sig	F	sig	F	sig	F	sig	F	sig	F	sig	F	sig	F	sig
GS	1	17.50	***	237.32	***	23.60	***	2.27	ns	99.58	***	242.36	***	144.89	***	149.16	***
L	3	202.12	***	812.08	***	238.97	***	23.85	***	613.25	***	1030.35	***	760.77	***	786.41	***
Gen	2	1196.43	***	86.91	***	6482.88	***	1082.43	***	2921.15	***	93.57	***	3096.04	***	3180.02	***
PL	2	21.91	***	355.58	***	3.35	ns	64.19	***	342.20	***	308.44	***	313.74	***	324.86	***
NP	2	126.01	***	31.43	***	130.71	***	39.91	***	909.69	***	3.88	ns	1063.88	***	1093.22	***
GS×Gen	2	0.06	ns	10.15	***	0.38	ns	0.01	ns	11.89	***	7.85	***	17.06	***	17.33	***
GS×L	3	2.99	*	21.10	***	3.88	**	0.50	ns	13.10	***	21.27	***	24.35	***	24.94	***
GS×NP	2	0.15	ns	5.22	**	0.24	ns	0.89	ns	1.67	ns	6.40	**	4.23	*	3.22	*
GS×PL	2	2.59	ns	2.73	ns	2.87	ns	0.08	ns	3.72	*	2.06	ns	5.13	**	4.85	**
L×Gen	6	13.30	***	6.81	***	11.12	***	5.24	***	15.55	***	5.87	***	27.87	***	24.81	***
L×NP	6	1.94	ns	2.14	*	2.01	ns	0.36	ns	1.87	ns	1.48	ns	0.83	ns	1.24	ns
L×PL	6	0.47	ns	25.21	***	0.61	ns	0.97	ns	1.82	ns	25.67	***	4.00	***	4.34	***
Gen×NP	4	16.99	***	2.63	*	16.53	***	2.40	*	7.68	***	0.49	ns	72.96	***	72.46	***
Gen×PL	4	3.11	*	2.49	*	2.96	ns	11.43	***	30.45	***	6.11	**	183.59	***	198.38	***
PL×NP	4	14.19	***	9.03	***	16.90	***	1.90	ns	67.37	***	18.75	***	22.10	***	22.30	***
Residuals	432																

The table columns report the Fisher F (F) and the significance levels: * = 0.05, ** = 0.01, *** = 0.001, ns = not significant.

The protein yield was dominantly affected by L, followed by PL, GS, Gen, and NP. Additionally, protein yield was affected, in decreasing order, by all the first-order interactions with the exception of GS×PL. The highest average protein yield value was measured in DLN7, which was significantly higher than KBL13 and ZRDNA (Table 6). Moreover, this study indicated that PL (from PL60 to PL120) and NP (from NP1 to NP1.5) significantly increased the average protein yield by 31% and 8.1%, respectively. The highest protein yield was observed in BGL, followed by HLM and BLK, while HRT showed the lowest protein yield.

The gluten concentration was significantly affected in decreasing order by Gen, L, NP, and GS. Furthermore, gluten concentration was influenced in decreasing order by the first-order interactions PL×NP, Gen×NP, L×Gen, and GS×L, respectively. As the NP increased, gluten concentration significantly increased, with an increment of 4.5% from NP1 to NP1.5. The average gluten concentration was significantly higher at BGL, while no significant differences were observed between BLK, HLM, and HRT.

According to the ANOVA, Gen was the main factor for W, followed by PL, NP, and L. Additionally, W was significantly affected by the first-order interactions Gen×PL, L×Gen, and Gen×NP, in decreasing order, respectively. The maximum W value was measured in ZDNA, followed by DLN7, while the lowest W was measured in KBL13. As PL and NP increased, W significantly increased, with an increment of 5% and 4%, from PL60 to PL120 and from NP1 to NP1.5, respectively. The highest average W value was measured in HRT, which was significantly higher than BGL, but it was similar to HLM and BLK.

The starch concentration was strongly influenced by Gen, followed by NP, L, PL, and lastly GS. Additionally, starch concentration was strongly affected by the first-order interactions, particularly PL×NP, Gen×PL, GS×Gen, GS×L, and GS×PL, respectively, in decreasing order. The highest average starch concentration was measured in KBL13, followed by DLN7, while the lowest starch concentration value was measured in ZDNA. As the PL increased, the average starch concentration value increased, with an increment of 1.3% from PL60 to PL120. On the contrary, as the NP ratio increased, the average starch concentration value significantly decreased by 2.03% from NP1 to NP1.5. Furthermore, the highest average starch concentration value was measured at BGL, while the lowest was measured at HRT. BLK and HLM statistically showed similar starch concentration values, which were lower than BGL and higher than HRT, except no significant differences occurred between HLM and HRT.

Table 6. Average values of grain quality parameter mean values (standard error in brackets) of 3 common wheat varieties as a function of genotype (Gen), phosphorus (PL), nitrogen ratio (NP), location (L), and growing season (GS). Protein concentration (PC), protein yield (PY), gluten concentration (GC), dough strength (W), starch content (ST), starch yield (STY), amylopectin concentration (AP), and amylose to amylopectin ratio (AM:AP).

Variable Source	PC (%)		PY (kg ha^{-1})		GC (%)		W (10^{-4} J)		ST (%)		STY (t ha^{-1})		AP (%)		AM:AP (%)	
	Average	sig	Average	sig	Average	sig	Average	sig	Average	sig	Average	sig	Average	sig	Average	sig
GS		***		***		***		***		***		***		***		***
DLN7	11.38 (0.13)	b	594.42 (43.47)	a	7.98 (0.09)	b	84.17 (1.26)	b	80.5 (0.29)	b	4.25 (0.35)	a	80.59 (0.22)	a	24.10 (0.35)	c
KBL13	10.5 (0.15)	c	520.47 (35.36)	b	6.95 (0.10)	c	73.35 (1.14)	c	82.52 (0.29)	a	4.14 (0.33)	a	78.7 (0.22)	c	27.07 (0.32)	a
ZDNA	11.96 (0.12)	a	550.21 (42.20)	b	9.35 (0.10)	a	90.69 (1.32)	a	79.62 (0.36)	c	3.69 (0.31)	b	79.51 (0.22)	b	25.78 (0.34)	b
PL (kg ha^{-1})		***		*		ns		***		***		***		***		***
PL60	11.17 (0.21)	b	474.09 (30.45)	c	8.04 (0.26)		80.31 (1.99)	b	80.38 (0.37)	c	3.45 (0.25)	c	78.31 (0.33)	b	26.11 (0.52)	a
PL90	11.30 (0.2)	ab	568.12 (41.84)	b	8.11 (0.27)		83.59 (2.19)	a	80.87 (0.42)	b	4.11 (0.34)	b	79.58 (0.29)	ab	25.67 (0.44)	b
PL120	11.36 (0.21)	a	622.89 (40.76)	a	8.13 (0.29)		84.31 (2.39)	a	81.39 (0.5)	a	4.52 (0.35)	a	79.91 (0.25)	a	25.16 (0.39)	c
NP		***		***		**		***		***		ns		***		***
1	11.02 (0.2)	b	536.38 (42.46)	b	7.91 (1.8)	b	80.86 (2.1)	b	81.74 (0.42)	a	4.03 (0.36)		80.15 (0.29)	a	24.79 (0.45)	c
1.25	11.32 (0.19)	a	548.88 (38.62)	ab	8.12 (1.87)	ab	83.23 (2.21)	a	80.82 (0.4)	b	3.96 (0.31)		79.61 (0.27)	ab	25.63 (0.42)	b
1.5	11.49 (0.21)	a	579.84 (41.80)	a	8.25 (1.88)	a	84.12 (2.33)	a	80.08 (0.41)	c	4.08 (0.33)		79.04 (0.25)	b	26.53 (0.40)	a
L		***		***		***		***		***		***		***		***
BGL	10.78 (0.24)	c	740.05 (38.72)	a	7.71 (0.31)	b	80.62 (2.67)	b	82.01 (0.41)	a	5.65 (0.31)	a	78.83 (0.25)	c	26.88 (0.41)	a
BLK	11.34 (0.18)	b	519.60 (22.8)	b	8.14 (0.27)	a	82.87 (2.33)	ab	80.74 (0.42)	b	3.71 (0.16)	b	79.75 (0.31)	b	25.42 (0.48)	b
HLM	11.43 (0.2)	ab	530.59 (31.47)	b	8.21 (0.29)	a	83.37 (2.27)	a	80.56 (0.46)	bc	3.75 (0.23)	b	79.74 (0.29)	b	25.42 (0.44)	b
HRT	11.57 (0.19)	a	429.9 (28.15)	c	8.32 (0.28)	a	84.1 (2.23)	a	80.21 (0.47)	c	2.99 (0.21)	c	80.09 (0.31)	a	25.89 (0.48)	b
GS		***		***		***		ns		***		***		***		***
2021	11.53 (0.19)	a	519.54 (36.03)	b	8.14 (0.25)	a	82.97 (2.04)		80.72 (0.41)	b	3.75 (0.3)	b	79.72 (0.28)	a	25.46 (0.43)	b
2022	11.30 (0.18)	b	590.53 (36.65)	a	8.05 (0.25)	b	82.51 (2.01)		81.04 (0.39)	a	4.30 (0.3)	a	79.48 (0.26)	b	25.84 (0.40)	a

The table columns report the significance levels: * = 0.05, ** = 0.01, *** = 0.001, ns = not significant. Letters represent the Tukey HSD post hoc test results.

Furthermore, L was the dominant factor for starch yield, followed by PL, GS, and Gen. Starch yield was not influenced by NP. Additionally, starch yield was strongly affected by the first-order interactions, such as L×PL, GS×L, PL×NP, GS×Gen, Gen×PL, GS×NP, and L×Gen, respectively, in decreasing order. The DLN7 showed the highest average starch yield, followed by KBL13, while the lowest starch yield was measured in ZDNA. The higher average starch yield was determined at BGL, followed by HLM and BLK, in decreasing order, while the lower starch yield was observed in HRT. Moreover, starch yield significantly increased by 31% as PL application increased from PL60 to PL120. The Gen was a dominant factor for AP and AM:AP, followed by NP, L, PL, and GS (Table 5). Additionally, AP was significantly affected by the first-order interactions, in particular, Gen×PL, Gen×NP, L×Gen, GS×L, PL×NP, GS×Gen, GS×PL, GS×NP, and lastly L×PL, respectively, in decreasing order. Similarly, AM:AP was significantly influenced by the first-order interactions of GS×PL, Gen×NP, GS×L, L×Gen, GS×Gen, GS×PL, L×PL, and GS×NP, respectively, in decreasing order.

The maximum average amylopectin value was determined in DLN7, followed by ZDNA, while the poorest amylopectin concentration value was determined at KBL13 (Table 6). On the contrary, the maximum average AM:AP value was determined in KBL13, followed by ZDNA, and the lowest AM:AP value was measured at DLN7. As the PL increased, the average amylopectin concentration value was significantly increased by 2%, but the AM:AP value decreased by 3.63%, from PL60 to PL90. Contrastingly, as the NP ratio increased, the average amylopectin concentration value significantly decreased by 1.4%, but the AM:AP value significantly increased by 6.55%, from NP1 to NP1.5 (Table 6). Furthermore, the maximum average amylopectin concentration value was measured in HRT, while the smallest amylopectin concentration value was observed at BGL; but HLM and BLK showed similar amylopectin concentration values, significantly lower than HRT and higher than BGL. Likewise, the maximum average AM:AP value was observed at BGL, a significant difference from the other locations. No significant differences occurred between BLK, HLM, and HRT for AM:AP. The PL interaction with NP needs to be further analyzed. At PL60, protein concentration was not significantly affected by NP, while at PL90 and P120, protein concentration increased by 3.35% and 6.57% from NP1 to NP1.5, respectively (Figure 3A). Likewise, at PL60 and PL90, the gluten concentration trend showed a relative increase, as NP ratios increased but were statistically non-significant. Instead, gluten concentration significantly increased by 6.77% at PL120, as NP ratios increased from NP1 to NP1.5.

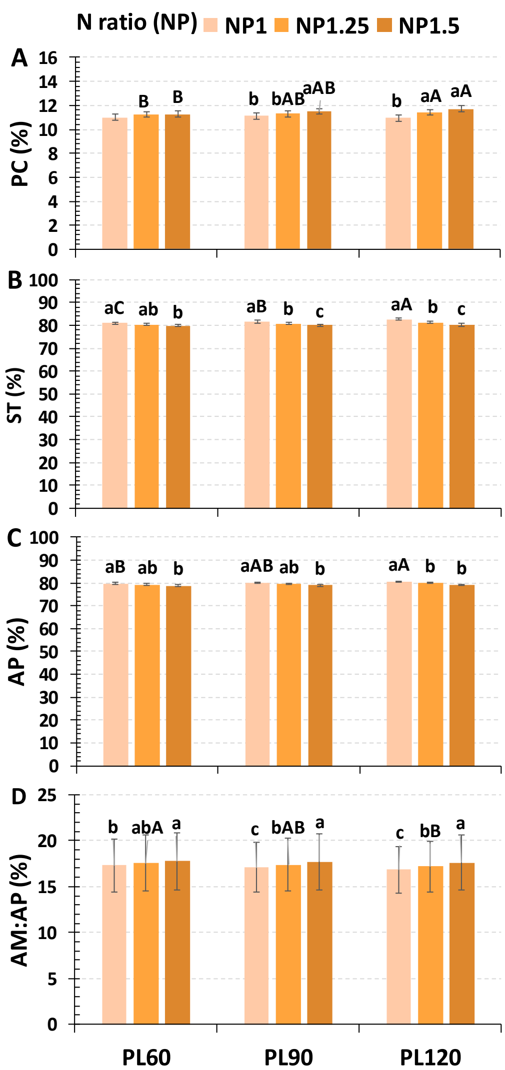

Figure 3. From top to bottom, the response of nitrogen ratio (NP) at the three levels of phosphorus (PL60, PL90, and PL120) on (**A**) protein content (PC), (**B**) starch content (ST), (**C**) amylopectin (AP), and (**D**) amylose to amylopectin ratio (AM:AP). Lowercase letters represent significant differences between NP ratios within the same level of phosphorus, and uppercase letters represent significant differences between phosphorus levels within the same NP ratio, according to the Tukey HSD post hoc test results.

Regarding protein yield and W, the only significant differences were found at the PL60 level with a combination of NP ratios, whereas the protein yield and W were increased by 15.3 and 4.76%, respectively, from NP1 to NP1.5. As the NP ratio increased from the NP1 to NP1.5 rate at the PL60, PL90, and PL120 levels, it decreased the starch concentration and amylopectin concentration value significantly, by 1.2, 1.88, and 3.11%, and 1.05, 1.44, and 1.72%, respectively (Figure 3B,C). In contrast, the AM:AP value increased significantly by 2.55, 3.41, and 4.16% at PL60, PL90, and PL120 levels, respectively, as the NP ratio increased from NP1 to NP1.5 (Figure 3D). Regarding starch yield, the NP treatments were only significant at the PL60 level, in which the starch yield increased by 12.1% from the NP1 to N1.5 level.

The PL and NP interaction with Gen needs to be further analyzed (Figure 4). The protein concentration increased significantly up to the application of PL90 at KBL13 and ZDNA, but no significant difference was found between PL90 and PL120 (Figure 4A).

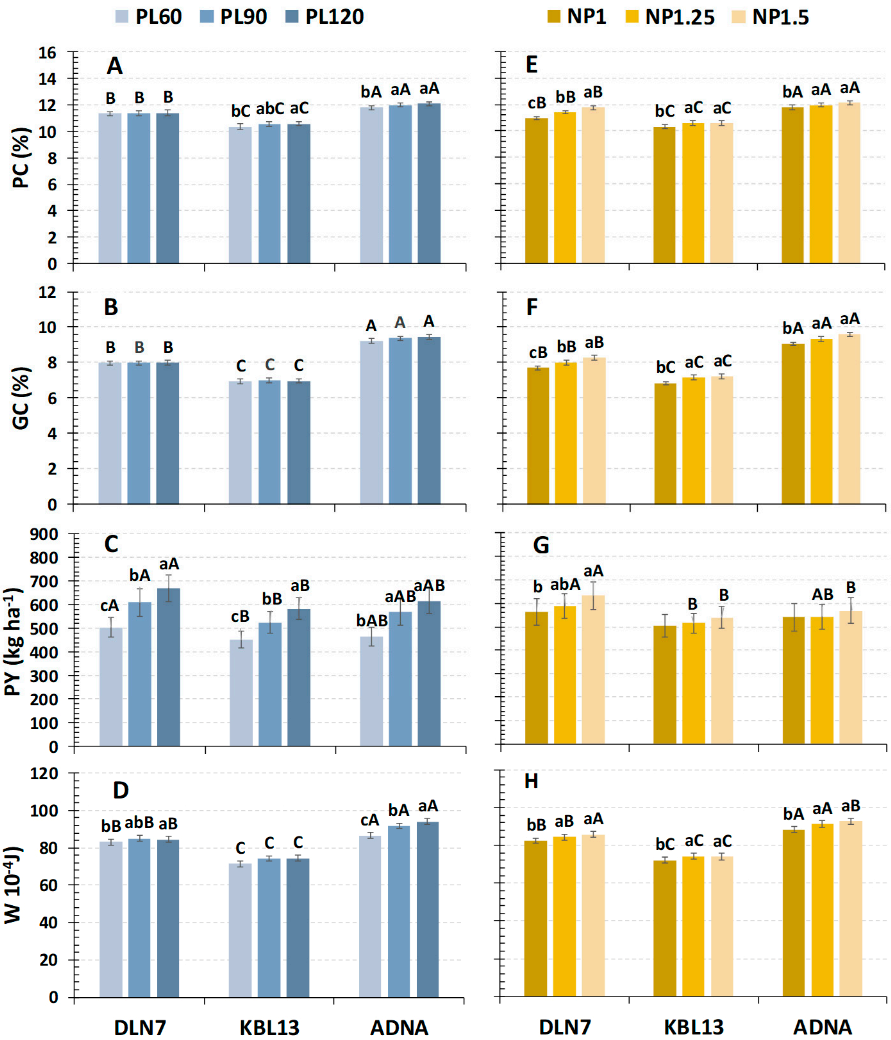

Figure 4. Left diagram: from top to bottom, the performance of phosphorus levels (PL), on three varieties (Gen, DLN7, KBL13, and ZDNA), on (**A**) protein content (PC), (**B**) gluten content (GC), (**C**) protein yield (PY), and (**D**) dough strength (W). Right diagram: from top to bottom, the performance of nitrogen ratios (NP), on three varieties (Gen, DLN7, KBL13, and ZDNA), on (**E**) protein content (PC), (**F**) gluten content (GC), (**G**) protein yield (PY), and (**H**) dough strength (W). Lowercase letters represent significant differences between phosphorus level (PL) and nitrogen ratio to PL (NP) within the same variety, and uppercase letters represent significant differences between varieties within the same PL and NP level, according to the Tukey HSD post hoc test results.

Additionally, the PL treatment did not influence the protein concentration in DLN7. The gluten concentration value tended to increase by 2.57% and 0.4% at ZDNA and KBL13, respectively, after the supply of PL120 compared to PL60, but it was not statistically significant (Figure 4B). Interestingly, the protein yield significantly increased by 32.9%, 28.8%, and 30.8% at DLN7, KBL13, and ZDNA, respectively, as PL increased from PL60 to PL120 (Figure 4C). Moreover, W significantly increased by 8.65% and 1.77% at ZDNA and DLN7, respectively, as PL increased from PL60 to PL120; but W was not affected at KBL13 under the PL treatment (Figure 4D).

The protein concentration and gluten concentration increased as NP increased up to NP1.25 in KBL13 and ZDNA, while no significant increment was observed with the further application of NP in both Gen. Instead, at DLN7, protein concentration and gluten concentration increased significantly with increased NP, by an increment of 7.2% and 7.33% from NP1 to NP1.5, respectively (Figure 4E,F). The protein yield increased by 12.2% at DLN7 after the application of NP1.5 compared to NP1. Additionally, the trend of protein yield linearly increased at KBL13 and ZDNA as the NP rate increased, but it was not statistically significant (Figure 4G). Furthermore, the W value increased significantly as the NP ratio increased up to NP1.25 for all the Gen; however, no significant differences occurred between NP1.25 and NP1.5 (Figure 4H).

The PL and NP interaction with Gen significantly affected starch concentration, amylopectin concentration, and AM:AP (Figure 5). The starch concentration values increased by 0.72%, 1.92%, and 2.04% at DLN7, KBL13, and ZDNA, respectively, as PL increased from PL60 to PL120 (Figure 5A). Similarly, starch yield strongly increased by 33.70% (4.8 t ha^{-1}), 28.42% (4.6 t ha^{-1}), and 30.88% (4.11 t ha^{-1}) at DLN7, KBL13, and ZDNA, respectively, after the application of PL120 compared to PL60 (Figure 5B). Furthermore, amylopectin concentration increased by 1.94% and 0.3% at KBL13 and ZDNA, respectively, as PL increased from PL60 to PL120, but amylopectin concentration showed no response at DLN7 under the PL treatment (Figure 5C). Additionally, AM:AP at DLN7 and ZDNA showed no response to PL treatment, but AM:AP decreased significantly by 8.5% at KBL13 after the supply of PL120 compared to PL60 (Figure 5D). On the contrary, starch concentration decreased significantly under NP treatment, by 2.29%, 1.65%, and 2.26% at DLN7, KBL13, and ZDNA, respectively, as NP increased from NP1 to NP1.5 (Figure 5E,F). Additionally, NP treatment did not influence starch yield in any of the varieties (Figure 5E,F). Furthermore, amylopectin concentration significantly decreased by 1.37%, 0.78%, and 2.1% at DLN7, KBL13, and ZDNA, respectively, at the highest NP ratio compared to the lowest NP ratio (Figure 5G). Interestingly, AM:AP significantly increased by 7.25%, 3.77%, and 10.36% at DLN7, KBL13, and ZDNA, respectively, as NP increased from NP1 to NP1.5 (Figure 5H).

The PL interaction with L needs to be further analyzed. Although protein concentration, gluten concentration, and starch concentration were not significantly affected by PL application for all locations (Figure 6), W, protein yield, starch yield, amylopectin concentration, and AM:AP showed significant increases with PL application at all considered locations. W significantly increased as PL increased from PL60 to PL90 at BGL, BLK, and HLM, but no further significance was detected between PL90 and PL120. However, W was not influenced in HRT under the PL treatment. Moreover, the data showed that as PL increased, protein yield and starch yield significantly increased. The protein yield increments were 44.43%, 22.08%, 22.24%, and 37.40%, and starch yield increments were 42.21%, 22.1%, 22.23%, and 37.6%, in BGL, BLK, HLM, and HRT, respectively, from PL60 to PL120 (Figure 6A,B). Furthermore, amylopectin concentration increased by 0.76%, 0.97%, and 0.71% at BGL, BLK, and HLM, respectively, with the highest PL compared to the lowest PL. However, amylopectin concentration showed no response at HRT under the PL treatment (Figure 6C). Lastly, the results showed that as the PL rate increased, the AM:AP value was significantly reduced, by 3.66%, 4.7%, 3.42%, and 2.87%, in BGL, BLK, HLM, and HRT, respectively. However, the reduction value at HRT was not statistically significant (Figure 6D).

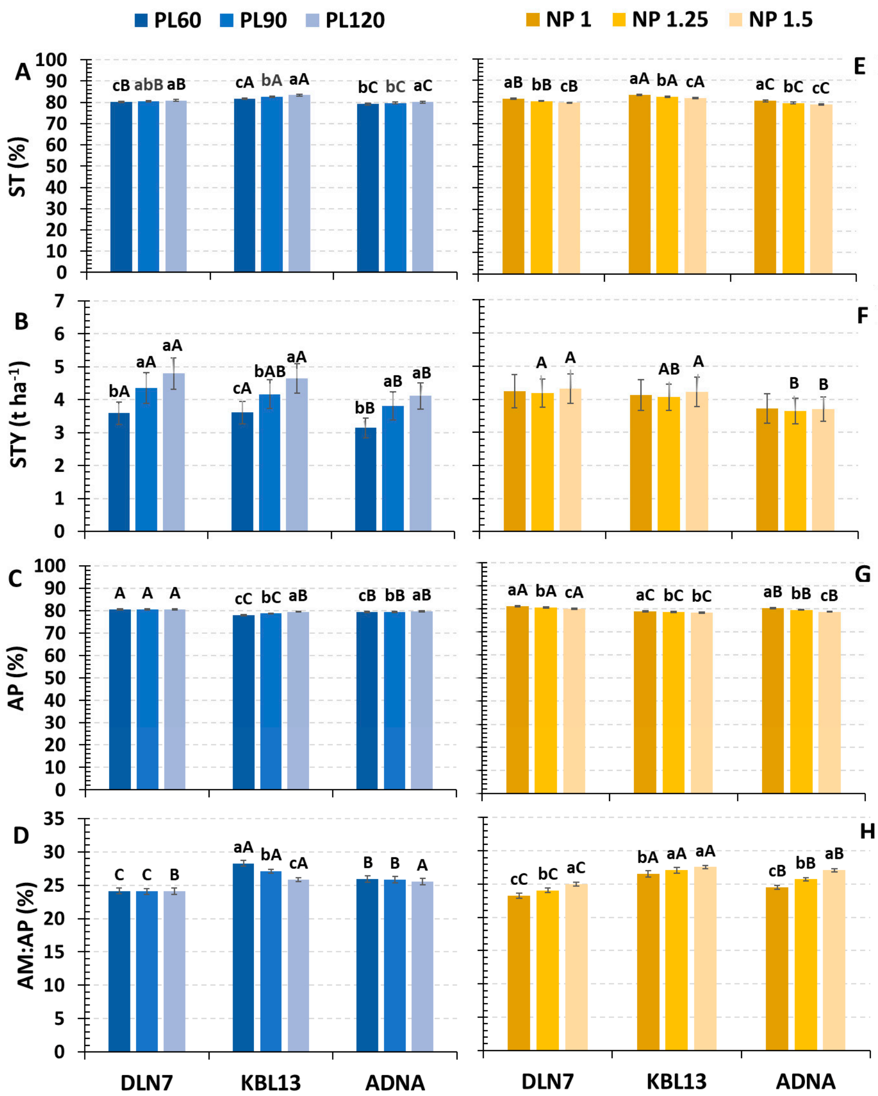

Figure 5. Left diagram: from top to bottom, the performance phosphorus levels (PL), on three varieties (Gen, DLN7, KBL13, and ZDNA), on (**A**) starch content (ST), (**B**) starch yield (STY), (**C**) amylopectin (AP), and (**D**) amylose to amylopectin ratio (AM:AP). Right diagram: from top to bottom, the performance of nitrogen ratio (NP), on three varieties (Gen, DLN7, KBL13, and ZDNA), on (**E**) starch content (ST), (**F**) starch yield (STY), (**G**) amylopectin (AP), and (**H**) amylose to amylopectin ratio (AM:AP). Lowercase letters represent significant differences between PL and NP within the same variety, and uppercase letters represent significant differences between varieties within the same PL and NP according to the Tukey HSD post hoc test results.

The GBRT model was applied to determine the relative contribution of soil, climate, and management parameters to grain yield, protein concentration, gluten concentration, starch concentration, and W (Figure 7). The relative contribution of soil and management factors to grain yield production was almost equal (39.15% and 38.85%, respectively), while climate contributed 22% to grain yield variability. The relative contribution of pH, PL, P_TGf, and Gen on grain yield was 18.4%, 16.84%, 12.75%, and 12%, respectively, with OM, NP, GDD_TGf, and Av_P contributing less than 12%. Moreover, management had a higher relative contribution to protein concentration and gluten concentration (65.96% and 83.8%, respectively) compared to soil and climate parameters (protein concentration, 81.9% and 15.95%, and gluten concentration, 8.6% and 7.52%, respectively). The Gen was the most influential factor for protein concentration and gluten concentration accumulation (relative contribution = 40.6% and 72.8%, respectively), with NP, PL, and GDD_TGf contributing 14%, 11.41%, and 11% to protein concentration, respectively. pH, P_TGf, Av_P, and OM showed contributions lower than 11% for protein concentration, while NP and GDD_TGf explained 6.3% and 5.14% of the gluten concentration, respectively, and PL, P_TGf, Av_P, OM, and pH had contributions lower than 5%. Likewise, management had the highest relative contribution to starch concentration and W variability (72.03% and 68.32%, respectively), compared to soil and climate parameters (ST, 17.02% and 11%; W, 13% and 18.17%). The Gen was the most influential parameter affecting starch concentration and W (relative contribution = 43.73% and 44.19%, respectively). The NP, pH, and PL contributed 16.75%, 14.68%, and 11.55% to starch concentration, respectively, while GDD_TGf, P_TGf, Av_P, and OM had contributions lower than 7%. W, PL, NP, and GDD_TGf explained 12.8%, 11.33%, and 10.6% of the variability, respectively, while P_TGf, Av_P, OM, and pH had contributions lower than 9%.

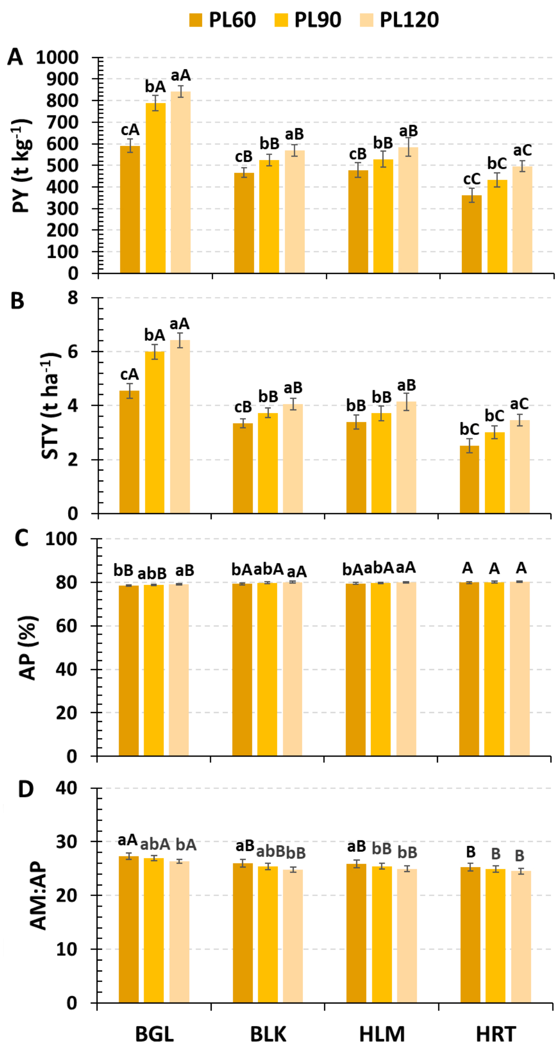

Figure 6. From top to bottom, the performance of three phosphorus levels (PL) in four locations (BGL: Baghlan, BLK: Balkh, HLM: Helmand, and HRT: Herat) on (**A**) protein yield (PY), (**B**) starch content (ST), (**C**) amylopectin (AP), and (**D**) amylose to amylopectin ratio (AM:AP). Lowercase letters represent significant differences between PL within the same location, and uppercase letters represent significant differences between locations within the same PL, according to the Tukey HSD post hoc test results.

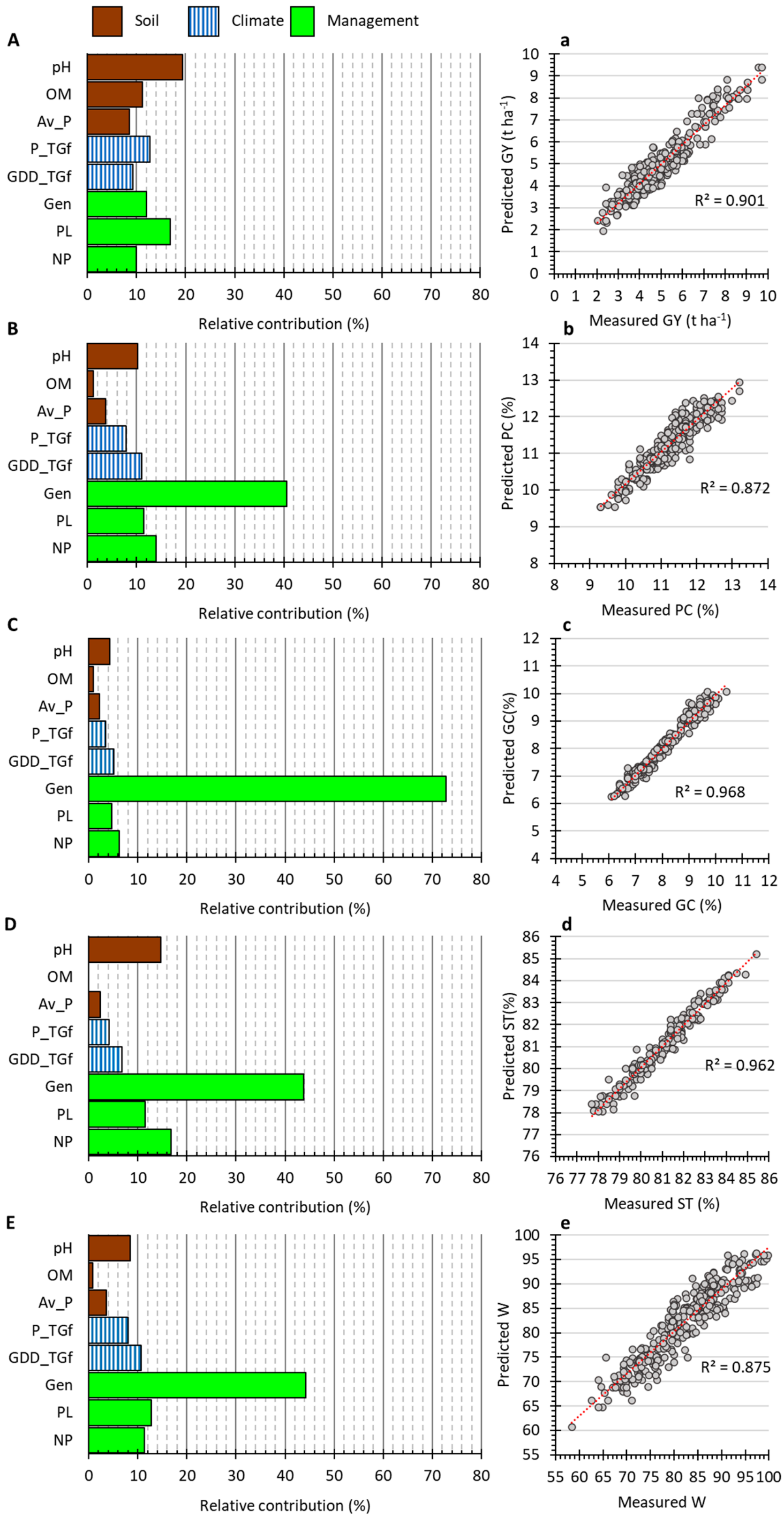

Figure 7. The relative contribution (%) of predictor parameters for the boosted regression tree model (BRTM) of grain yield (SY), protein content (PC), gluten content (GC), starch content (ST), and dough strength (W) is shown in (**A**–**E**), respectively. Measured and predicted annual GY, PC, GC, ST, and W with the BRTM model using predictors shown in (**a**–**e**), respectively. The red line represent the line of best fit.

The soil pH showed a significant negative correlation with OM, Tot_N, Av_P, and Av_K (Table 7). OM, Tot_N, Av_P, and Av_K were positively correlated with each other. GDD_TGf was positively correlated with Tot_N, Av_K, Av_P, and OM, but negatively correlated with pH. In contrast, P_TGf showed a negative correlation with Tot_N, Av_K, Av_P, OM, and GDD_TGf, but a positive correlation with pH. Grain yield, straw yield, protein yield, starch concentration, starch yield, and AM:AP showed strong negative correlations with pH but were positively correlated with Tot_N, Av_K, Av_P, and OM. Conversely, protein concentration, gluten concentration, and W were positively correlated with pH but negatively correlated with Tot_N, Av_K, Av_P, and OM. Additionally, grain yield, straw yield, protein concentration, protein yield, starch yield, and W showed positive correlations with both PL and NP, while starch concentration, amylopectin concentration, and AM:AP were negatively correlated with NP but positively correlated with PL. The correlation of TKW with both PL and NP was not significant, but the correlation of gluten concentration was significant, being positive with NP and negative with PL.

Table 7. Correlation between soil parameters (including pH, organic matter (OM), available phosphorus (AV_P), available potassium (AV_K), and total nitrogen (Tot_N)), climate parameters (including growing degree days (GDD_TGF) and precipitation amount (P_TGF) accumulated between tillering and grain filling), and agronomic traits (including straw yield (SY), grain yield (GY), thousand grain weight (TKW), protein concentration (PC), protein yield (PY), gluten concentration (GC), starch concentration (ST), starch yield (STY), amylopectin (AP), amylose to amylopectin ratio (AM:AP), and dough strength (W)). The values reporting the correlation significance are as follows: *** = 0.0001, ** = 0.001, * = 0.05, ns = not significant.

	pH	OM (%)	AV_P (mg kg^{-1})	AV_K (mg kg^{-1})	Tot_N (%)	GDD_TGf (°C)	P_TGf (mm)	PL (kg ha^{-1})	NP	GY (t ha^{-1})	SY (t ha^{-1})	TKW (g)	PC (%)	PY (t ha^{-1})	GC (%)	ST (%)	STY (t ha^{-1})	AP (%)	AM:AP	W (10^{-4} J)
pH	−0.95 ***	−0.85 ***	−0.89 ***	−0.86 ***	−0.22 ***	−0.2 ***	0, ns	0, ns	−0.67 ***	−0.75 ***	0.04, ns	0.36 ***	−0.71 ***	0.21 ***	−0.38 ***	−0.75 ***	0.4 ***	−0.4 ***	0.14 ***	−0.95 ***
OM (%)		1	0.9 ***	0.92 ***	0.95 ***	0.46 ***	0.09 *	0, ns	0, ns	0.7 ***	0.71 ***	0.12 **	−0.33 ***	0.68 ***	−0.19 ***	0.35 ***	0.71 ***	−0.38 ***	0.38 ***	−0.13 ***
AV_P (mg kg^{-1})			1	0.67 ***	0.99 ***	0.19 ***	0.21 ***	0, ns	0, ns	0.54 ***	0.7 ***	0.13 **	−0.35 ***	0.66 ***	−0.2 ***	0.37 ***	0.7 ***	−0.38 ***	0.38 ***	−0.14 ***
AV_K (mg kg^{-1})				1	0.75 ***	0.6 ***	−0.01, ns	0, ns	0, ns	0.73 ***	0.61 ***	0.08 *	−0.27 ***	0.59 ***	−0.16 ***	0.29 ***	0.61 ***	−0.32 ***	0.32 ***	−0.11 **
Tot_N (%)					1	0.34 ***	0.14 ***	0, ns	0, ns	0.6 ***	0.69 ***	0.18 ***	−0.34 ***	0.66 ***	−0.19 ***	0.35 ***	0.69 ***	−0.37 ***	0.37 ***	−0.14 ***
GDD_TGf (°C)						1	−0.42 ***	0, ns	0, ns	0.46 ***	0.09 *	0.4 ***	0.01, ns	0.11 **	0, ns	0, ns	0.08 *	−0.04, ns	0.04, ns	0, ns
P_TGf (mm)							1	0, ns	0, ns	0.08, ns	0.34 ***	0.16 ***	−0.17 ***	0.32 ***	−0.1 *	0.19 ***	0.34 ***	−0.18 ***	0.18 ***	−0.07, ns
PL (kg ha^{-1})								1	0, ns	0.3 ***	0.34 ***	0.01, ns	0.1 *	0.38 ***	0.03, ns	0.24 ***	0.34 ***	0.22 ***	−0.22 ***	0.19 ***
NP									1	0.06, ns	0.05, ns	0, ns	0.24 ***	0.11 **	0.13 ***	−0.4 ***	0.02, ns	−0.4 ***	0.4 ***	0.15 ***
GY (t ha^{-1})										1	0.77 ***	0.12 **	−0.28 ***	0.76 ***	−0.23 ***	0.38 ***	0.77 ***	−0.21 ***	0.21 ***	−0.1 **
SY (t ha^{-1})											1	0.07, ns	−0.39 ***	0.97 ***	−0.3 ***	0.51 ***	1 ***	−0.29 ***	0.3 ***	−0.13 ***
TKW (g)												1	0, ns	0.08 *	−0.01, ns	−0.01, ns	0.06, ns	0.04, ns	−0.05, ns	0, ns
PC (%)													1	−0.16 ***	0.92 ***	−0.87 ***	−0.43 ***	0.34 ***	−0.35 ***	0.8 ***
PY (t ha^{-1})														1	−0.09 *	0.32 ***	0.95 ***	−0.23 ***	0.23 ***	0.07, ns
GC (%)															1	−0.83 ***	−0.35 ***	0.26 ***	−0.26 ***	0.85 ***
ST (%)																1	0.55 ***	−0.24 ***	0.24 ***	−0.68 ***
STY (t ha^{-1})																	1	−0.3 ***	0.3 ***	−0.17 ***
AP (%)																		1	−1 ***	0.34 ***
AM:AP																			1	−0.35 ***
W (10^{-4} J)																				1

4. Discussion

Afghanistan is characterized by an arid and semi-arid climate, with an annual average precipitation ranging between 200 and 400 mm [33]. Due to insufficient precipitation, the soil in Afghanistan contains a high amount of calcium carbonate, resulting in high pH values and low soil organic matter content ranging from 0.2 to 2.5% [34,35]. These soil conditions, particularly the poor availability of Av_P, Tot_N, and OM, have contributed to low crop yields on calcareous soils in Afghanistan [8]. The study's findings indicate that both soil and climate factors can influence straw yield and grain yield, similar to the management factor. However, the management factor played a more prominent role in determining protein concentration, gluten concentration, protein yield, starch concentration, starch yield, amylopectin concentration, AM:AP, and W compared to the effects of soil and climate factors.

Since the trials were irrigated at the four locations, the influence of P_TGf on common wheat quality characteristics was explained to have smaller variability compared to the factors of GDD_TGf, pH, and management. Our results suggest that irrigation can both mitigate the deficit stress of P_TGf during the growing season and prolong the possibility of GDD_TGf to accumulate more biomass. Other studies by Latief et al. (2018) and Man et al. (2016) [36,37] have highlighted the significant impact of irrigation on wheat yield and quality. However, it is crucial to apply an appropriate amount of water to maintain wheat yield and quality, avoiding excessive or inadequate irrigation to prevent surface water scarcity and groundwater depletion during the growing season. These findings hold great value for improving Afghan agriculture production, encompassing both quantity and quality. As irrigated crop production plays a central role in ensuring food security, job creation, and household income, the information presented here can assist Afghan wheat growers in making informed decisions on managing their wheat fields under the arid and semi-arid Afghan climate, with soil characterized by high pH and $CaCO_3$ concentration. Poole et al. (2022) [6] reported that irrigated wheat productivity in Afghanistan is more than double that of rainfed wheat (2.5 compared with 1.09 t ha^{-1}). This result can serve as a valuable roadmap to support Afghan wheat growers in optimizing their cultivation practices and achieving better outcomes within the specific agricultural and environmental conditions of the region.

In this study, the results revealed that soil pH at the four locations had a more significant impact on straw yield, grain yield, protein concentration, protein yield, gluten concentration, starch concentration, starch yield, amylopectin concentration, AM:AP, and W compared to other soil parameters (OM and Av_P) and climate parameters (GDD_TGf and P_TGf). However, the effect of soil pH was comparable with PL and NP and lower than the effects of Gen. Soil pH plays a vital role in determining the availability of nutrients to plants, influencing the activity of soil fauna and biota, as well as affecting plant growth, yield, and crop quality. When soil pH is close to neutral, essential nutrients become more accessible to plants. In alkaline soils like HRT and BLK, higher pH levels can lead to reduced concentrations of Tot_N, Av_P, OM, and micronutrients. The results suggest that improving wheat productivity in Afghanistan could involve efforts to lower soil pH. However, it is important to note that using chemical elements such as sulfuric acid, sulfur, or grain yield psum to lower soil pH can be more expensive, especially in field crops like wheat. As an alternative, using salt-tolerant wheat varieties, implementing the banded application of P, and incorporating organic amendments could be recommended to enhance soil fertility and achieve a good yield and quality of irrigated wheat in Afghanistan. These recommendations align with similar findings reported by others [8,21,38].

The present study identified DLN7 as a superior genotype for grain yield, straw yield, TKW, protein yield, starch yield, and amylopectin concentration at all four locations, while ZDNA was superior for protein concentration, gluten concentration, and W, and KBL13 was superior for starch concentration and AM:AP. However, statistically, the difference between DLN7 and KBL13 was not significant for grain yield, straw yield, and starch yield. These results suggest that for a country like Afghanistan, where starvation and malnutrition are major challenges, DLN7 with a higher grain yield and amylopectin concentration content is recommended. On the other hand, KBL13 with a higher AM:AP ratio is preferable for promoting healthy consumption to mitigate disease incidences. Previous research has shown that the rapid digestion of starch is needed in cases of undernutrition and hunger, while slow and resistant digestion starches are more beneficial in addressing diabetes, gut diseases, blood pressure, and cardiovascular disorders [14]. Given that ZDNA has a higher protein concentration, gluten concentration, and W content, it is more suitable for baker production. Additionally, BLK13 was tested in a previous paper [21] during the 2016/2017 and 2017/2018 growing seasons, but it yielded relatively lower results (average of both GS: 4.37 t ha^{-1}) compared to the results of this study. This difference could be attributed to higher precipitation in 2021 and 2022 than in the 2017 and 2018 growing seasons.

The present study indicates that P availability is a limiting factor for wheat production in Afghanistan. In Afghan soil, high pH values and $CaCO_3$ concentration dominate, and these chemical reactions control P availability in the soil. In arid climates like Afghanistan, P sorption by clay mineral surfaces increases significantly in the presence of high calcium ion content, pH values, and lower organic matter in soils.Furthermore, P fertilization significantly improves the starch concentration and amylopectin concentration of wheat, while on the contrary, P application tends to reduce the AM:AP significantly. However, variable effects on starch concentration, amylopectin concentration, and AM:AP in response to P fertilization have been reported by previous researchers. For example, Ni et al. (2012) [17] found that a P application of 160 kg ha^{-1} increased the average starch concentration by 13.95% and amylopectin concentration by 13.22% compared to the control PL, while the AM:AP significantly reduced under PL treatment. Li et al. (2013) and Zhang et al. (2018) [39,40] indicated that PL application can increase the starch concentration and amylopectin concentration in wheat kernels, but not all genotypes had the same response to PL fertilization. Additionally, these results are consistent with [41], where it was reported that the optimum protein concentration was measured at 90 kg P_2O_5 ha^{-1}, while the further application of P did not affect the protein concentration. However, these data are in contrast with [42,43], which showed that P fertilization tended to reduce the wheat protein concentration. Moreover, PL treatment significantly affects W, with the optimal W value observed at PL90, which was significantly higher than PL60 but statistically similar to PL120. Our results are consistent with a previous study that reported dough strength significantly improved with P fertilization [44].

Our results suggest that N fertilization may be used as a tool to improve protein and gluten concentration in common wheat production. These findings are consistent with those reported in previously published studies [45,46]. Furthermore, NP significantly improved the average production of protein yield. These results align with previous findings in common wheat varieties [29,30]. On the contrary, NP fertilization significantly reduces the starch and amylopectin concentration of wheat. However, variable effects in response to N treatment have been reported in the previous literature. For example, Litke et al. (2018) [47] found that a decrease in starch concentration of 1.39% and 6.85% was observed at 120 and 240 kg N ha^{-1}, respectively, compared to the control. Mariem et al. (2020) [48] reported that starch concentration decreased under higher N fertilization, but the concentration of soluble sugars in the grain increased significantly. This suggests that under high N conditions, grain carbohydrates tend to be stored as mono- and disaccharides (glucose, sucrose, and maltose), rather than as starch. Xiong et al. (2014) [49] found that an increase in N application leads to an increase in starch A granules but, conversely, reduces the starch B granules. In general, the interaction result of NP with PL indicated that the NP1/PL120 rates can be known as a breakpoint for grain yield and straw yield, while the NP1.5/PL12 can act similarly for protein concentration and gluten concentration.

5. Conclusions

Environmental factors, particularly the higher pH value in Afghanistan's soils, were identified as limiting factors for common wheat production. In such soils, nutrient availability and organic matter content are typically very low. Under these conditions, the application of organic amendments along with the banded application of P is highly recommended. The results showed that increased PL application led to increased grain yield, straw yield, protein yield, and starch yield production for all locations. Additionally, PL increased protein concentration and W without decreasing TKW and gluten concentration. NP was found to be the most important factor determining protein concentration, protein yield, gluten concentration, and W without negatively affecting grain yield, straw yield, and TKW, indicating potential for further improvement in N management. Regarding starch concentration properties, NP negatively affected total starch and amylopectin concentration in all varieties, but AM:AP significantly improved with NP treatment, while starch yield remained unaffected. On the other hand, starch concentration, amylopectin concentration, and starch yield were significantly increased with increased PL application, but AM:AP was not affected by PL treatment. The present results indicated that the NP1/PL120 combination optimized grain yield, straw yield, and starch and amylopectin concentrations. Meanwhile, NP1.5/PL120 strongly increased protein and gluten concentrations. However, further studies, including additional years and considering various pedoclimatic conditions, are needed to further evaluate the interaction between soil, climate, and agronomical management.

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