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Growth, yield performance and nitrogen use efficiency of wheat as affected by nitrogen fertilization under arid agro-climatic conditions

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Overuse of nitrogenous fertilizers and low productivity of cropping systems produce the lowest nitrogen use efficiencies (NUE) in Pakistan. The surplus nitrogen (N) causes environmental degradation and reduces farm profitability. There is a lack of consideration of NUE while setting yield targets and nitrogen fertilization rates. The NUE is an essential indicator for sustainable crop production. The NUE can be improved with optimum nitrogen application without compromising crop yields. To find out an optimum nitrogen level for high NUE in wheat under agro-climatic conditions of Multan, an RCBD experiment comprising six nitrogen fertilizer doses (0, 50, 100, 150, 200, and 250 kg ha^{-1}) was conducted during 2017-18 and 2018-19. Increasing levels of N increased the growth and yield attributes, while the maximum cost-benefit ratio was recorded at 150 kg N ha^{-1}. Higher N doses (200 and 250 kg N ha^{-1}) increased the biological yield but did not translate into grain yield, reducing the harvest index and cost-benefit ratio. Several N use efficiency indices were established, showing that 100 kg N ha^{-1} recorded the maximum nitrogen use efficiency. Partial factor productivity, internal efficiency, and physiological efficiency were maximum at a lower dose (50 kg N ha^{-1}). In contrast, agronomic efficiency, partial nitrogen balance, recovery efficiency, and NUE were maximum at 100 kg N ha^{-1}. Higher N doses (150-250 kg N ha^{-1}) reduced all the N use efficiency indices. It is concluded that with a yield objective of about 5 t ha^{-1} under the agro-climatic conditions of Multan, a nitrogen application of 100-150 kg N ha^{-1} will be the most economical and will produce the maximum nitrogen use efficiency for wheat.
Keywords: Nitrogen overuse, pollution, economics, balanced nutrition, nitrogen losses

INTRODUCTION

Judicious use of nitrogenous fertilizers is imperative for profitability in intensive cropping systems. However, overuse of nitrogen (N) decreases the profitability of a cropping system and contributes to environmental degradation. Regarding nitrogen use, Pakistan is among the top four countries (Shahzad *et al.,* 2019). From 1961 to 2014, nitrogen use in Pakistan increased much faster than the increase in yield. At the same time, Pakistan recorded the lowest nitrogen use efficiencies (NUE) for all major crops. Many nations have improved nitrogen use efficiencies with judicious use of nitrogen. Pakistan's lowest nitrogen use efficiencies result from the overuse of N fertilizers and low mean crop yields (Shahzad *et al.,* 2019). Nitrogen use in agriculture is a double-edged sword. It is essential for food security on the one hand, while nitrogen pollution is a severe threat to the climate in the 21st century and agriculture sustainability on the other hand (Aziz et al., 2022). NUE is a crucial indicator for establishing sustainable food security targets (Zhang et al., 2015). Without substantial improvement in NUE, the N fertilizer application will be required to increase by 60% to reach global food security targets (Ladha et al., 2016).

In Pakistan, wheat is a primary staple food, contributing 1.8% to GDP. During 2020-21, the wheat cultivated area increased from 8,805 thousand hectares to 9,178 thousand hectares. Wheat production increased by 8.1% compared to last year due to an increase in developed regions (Anonymous, 2021). However, mean wheat yields in Pakistan are meager, while using nitrogen fertilizers is very high, thus producing the lowest NUE for wheat globally (Shahzad *et al.,* 2019). Although nitrogen application is paramount to ensure crop yield (Liu *et al.,* 2010), many studies have reported that surplus nitrogen application can reduce yield instead of increasing it (Cassman, 1999). Low NUE could result from poor management of agronomic practices such as excessive use of N fertilizers, application method and timing, and imbalanced fertilizer use (Zhu *et al.,* 2005). The higher dose

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of nitrogen fertilizers decreases nitrogen use efficiency (NUE) and partial factor productivity (PFP), so the yield of produce declines (Zhao *et al.,* 2006; Tana *et al.,* 2015). The cropping system, soil, and climate also impact NUE. The socioeconomic conditions of a country also influence NUEs (Zhang *et al.,* 2015; Van *et al.,* 2015; Ferguson, 2015).

Nitrogen losses are the main reason for low NUE, such as volatilization, denitrification, nitrate leaching, and losses. In calcareous soils, nitrogen is lost by ammonia volatilization (Mandal *et al.,* 2018). Volatilization of nitrogen depends upon fertilizer management and environmental conditions like wind, temperature, and rainfall (Sommer *et al.,* 2004). Volatilization losses of nitrogen can be minimized by adequately applying fertilizers, soil moisture availability, and straw incorporation (Woodley *et al.,* 2018). Denitrification is the conversion of nitrate into gas forms (nitrogen monoxide, nitrous oxide, and nitrogen dioxide) by biological agents under limited oxygen. Nitrate leaching frequently occurs in sandy soils and soils with a net negative charge that cannot hold NO_3 ions (Di and Cameron, 2002). The leaching of nitrate depends upon the amount of applied nitrogen, nitrification rate, and denitrification (Cameron *et al.,* 2013). After nitrogen uptake and accumulation, loss of N through plants can also occur due to differences between nitrogen accumulation and assimilation (Xu *et al.,* 2012).

Climate change has become a serious threat to sustainable crop production. Overuse of nitrogen is one of the major causes of environmental pollution by losses such as evaporation, leaching, runoff, and increased emission of N gases (NH_3, N_2O, and NO) (Sutton *et al.,* 2011). N fertilizers significantly cause NH_3 emissions (Adhya *et al.,* 2016; Xu *et al.,* 2018). Surplus nitrogen increases the input cost and environmental pollution and reduces NUE. By improving NUE, crop yield can be enhanced with less harmful effects on the environment (Galloway *et al.,* 2008; Zhang *et al.,* 2015). The NUE is vital for improving crop quality and quantity and reducing fertilizer inputs and environmental pollution (Nabin *et al.,* 2022). To increase fertilizer efficiency, the use of balanced nutrients is more important. The right amount of nutrients maximizes crop harvest (Jan *et al.,* 2007). Optimum fertilizer application increases wheat yield (Rawal et al., 2016) and improves fertilizer use efficiency (Belete *et al.,* 2018a; Belete *et al.,* 2018b). There are opportunities to strengthen NUE through agronomic practices like irrigation management, the use of balanced crop nutrients, rotation with legumes, and the use of efficient fertilizers than the overuse of nitrogenous fertilizers (Shahzad *et al.,* 2019).

Since the green revolution, research has focused on increasing crop production using high inputs, particularly nitrogen fertilizers. Only recently, studies have emerged that the current N fertilizers and N application practices are highly inefficient, and much of the applied N pollutes the environment. There is also a big gap between the fertilizer recommendations and farmer practices. Farmers are inclined to use more N fertilizer to maximize profitability without understanding N overuse's inherent yield potential and negative consequences. Additionally, the fertilizer recommendations are designed only on the bases of soil organic matter without considering other yield-limiting factors and the overall yield potential. Pakistan produces an average wheat yield of 2.9 t ha^{-1} with average N application rates of 150 kg ha^{-1}, resulting in the lowest NUE of 35% (Shahzad et al., 2019). There is a need to create a delicate balance between fertilizer use and crop yield to improve the NUE. It was hypothesized that wheat NUE could be enhanced at low N application rates without sacrificing grain yield. Therefore, this study was designed to understand the relationship of yield performance with different NUE indices at varying N fertilizer application rates.

MATERIALS AND METHODS

***Experimental setup*:** The experiments were conducted at the experimental farm, Department of Agronomy, Bahauddin Zakariya University, Multan (71º30.74’ N; 30º15-64’ E). during 2017-18 and 2018-19. The climate of Multan is warm and semiarid. The average annual temperature of Multan is 25.6^{0}C, and the average yearly rainfall is 175 mm. Soil samples were randomly taken before sowing at a depth of 30 cm from three different places. Samples were dried, mixed, and analyzed. The soil texture was silty-clay with 3.41 dSm^{-1} EC and 8.2 pH. The topsoil contains 0.04% total nitrogen, 0.60% organic matter, 9.09 mg kg^{-1} soil Olsen phosphorus, and exchangeable potassium 145 mg kg^{-1} soil.

***Husbandry practices*:** The experiment was conducted according to RCBD with nitrogen as treatment. Six nitrogen levels (0, 50, 100, 150, 200, and 250 kg ha^{-1}) were added in three split applications. Fifty percent nitrogen was added at sowing, while the remaining two splits, each of 25%, were applied with first and second irrigation. Each experimental treatment had three replications. The experiment was repeated the following year with the same treatments and design. The meteorological data, i.e., daily mean maximum temperature, daily minimum temperature, and daily rainfall, are presented in Fig. 1.

Phosphoric and potassic fertilizers were applied as basal doses at 115 and 60 kg ha^{-1} as TSP and MOP, respectively. Wheat was sown (seed rate of 125 kg ha^{-1}) according to recommended production technology on a finely prepared seed bed in both experiments. Seeds were sown with a hand-driven seed drill, and the net plot size was 4.5*2 m^{-2}. The seeds were treated with Hombre XL at the rate of 2 ml/kg to free the crop from insect and disease attacks. All other agronomic practices were kept constant.

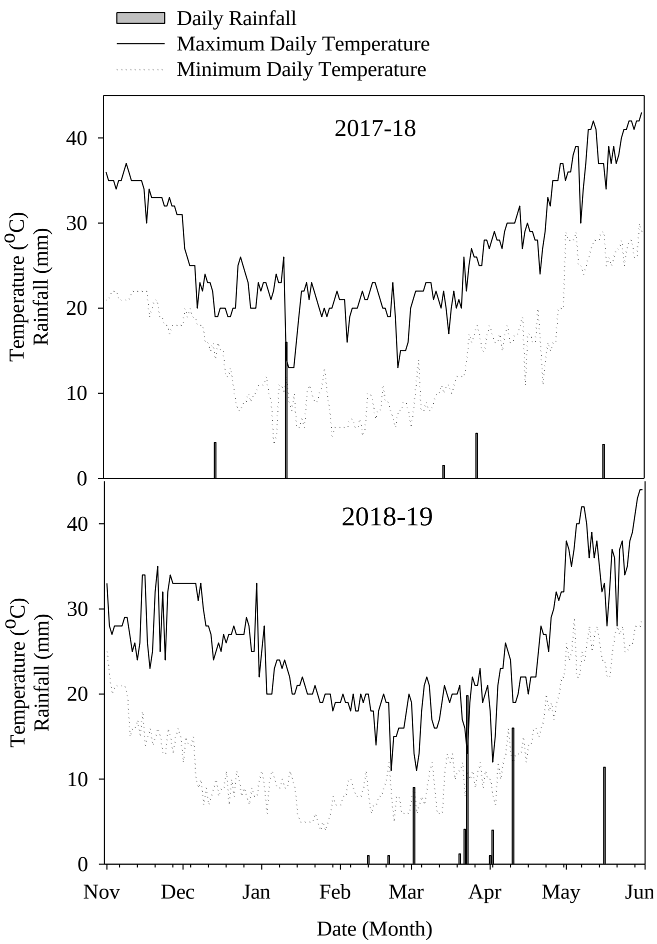

Figure 1. Meteorological data for crop seasons during 2017-18 and 2018-19.

***Harvesting and data collection*:** The crop was harvested manually at maturity, and each plot's grain yield and straw yield were measured and turned into tons per hectare. Other yield parameters were also measured, like plant height, no. of tillers, no. of fertile tillers, spike length, grains per spike, 1000 grain weight, and harvest index.

The NH_3-N was determined in plant tissues following the protocol of Martin *et al.* (1983). Briefly, plant tissue was ground into phosphate buffer (200 mM; pH 7.5). After liberation in Conway dishes by sodium tetraborate (pH 10) into the traps of 0.1 N HCI, the ammonia was diffused from the extract. The reaction was initiated with the addition of 200 µL sample, 1.0 mL of a solution containing 0.25 M Na_2HPO_4 in a 0.03% NaOCl, 1 mL of 0.17 mM Na-nitroprusside, and 0.125 N NaOH. On a Vortex mixer, the reaction was mixed and afterward incubated at 37ºC for 30 min in a water bath. The absorbance was recorded at 625 nm (Agilent Varian Cary 50).

Partial factor productivity (PFP) for nitrogen can be calculated as crop yield (kg) per unit of nitrogen application (kg) (Sarkar et al., 2021).

$$PFP = Y_A / Y_F \quad (1)$$

Agronomic efficiency for nitrogen (AEN) was calculated as an increase in grain yield (kg) per unit of nitrogen application (kg) (Sarkar *et al.*, 2021).

$$AEN = (YO - YF) / FA \quad (2)$$

The partial nitrogen balance (PNB) refers to the long-term viability of nitrogen uptake by the crop harvest per unit of nitrogen application (Ray *et al.*, 2018).

$$PNB = UA / FA \quad (3)$$

The internal efficiency of nitrogen (IEN) is calculated as grain yield per kg of nitrogen accumulation in plant dry mass (above-ground parts). The high value of IUE shows a nutrient deficiency. In contrast, the low value shows the inefficiency of conversion of internal nutrients due to various stresses (drought, heat, mineral toxicity, pest attack, and deficiency of other nutrients) (Liu *et al.*, 2011).

$$IEN = YA / UA \quad (4)$$

The recovery efficiency of nitrogen (REN) is the increase in nitrogen uptake by crop after nitrogen application (Dobermann, 2007; Liu *et al.*, 2011; Snyder and Bruulsema, 2007).

$$REN = (UA - UO) \times 100 / FA \quad (5)$$

Physiological efficiency for nitrogen (PEN) is the ratio of grain yield (kg) to nitrogen uptake (kg) in above-ground dry mass (Liu *et al.*, 2011; Snyder and Bruulsema, 2007).

$$PEN = (YA - YO) / (UA- UO) \quad (6)$$

Where Y_A = grain yield with nitrogen; Y_O = grain yield without nitrogen application; U_A = total nitrogen uptake with nitrogen applied; U_O = total nitrogen uptake without nitrogen application; F_A = nitrogen application; F_0 = no nitrogen application. PFP, IEN, PNB, AEN, and PEN are expressed as kg per kg, while REN is expressed as %age. All other parameters, such as fertilizer use, yield, and nutrient uptake, are measured in kg.

Nutrient use efficiency (NUE) was determined as the fraction of the nitrogen fertilizer that is utilized by the crop and allocated to nitrogen yield (Martinez-Feria *et al.*, 2018).

$$NUE = \text{Yield Nf} / \text{Fertilizer N} \quad (7)$$

***Economic analysis*:** The total cost of production (inputs) and total income gained by crop product (output) was calculated for economic analysis. To estimate total expenditure (input cost), land preparation, seed, fertilizers, irrigation, harvesting, and manual threshing costs were calculated according to market price. The gross income was obtained by multiplying the crop grain yield and straw yield with the market (local market) price of wheat grains and straw, respectively. To obtain net returns, total income was subtracted from gross income. The gross income was divided by the total cost to calculate the cost-benefit ratio.

***Statistical analysis*:** The analysis of variance (ANOVA) and Pearson's correlation among selected variables were performed on gathered data with the help of the statistical software Statistix 8.1. Treatment means were compared using the LSD (least significant difference) test at 5% P.

RESULTS

Table 1 describes the summary of the analysis of variance. The analysis shows that nitrogen treatments significantly affected all studied parameters. However, the treatment into year interactions was insignificant for plant height, yield components, harvest index, flag leaf, and grain N concentrations. Application of nitrogen fertilizer (0-250 kg ha^{-1}) significantly increased plant height up to 150 kg ha^{-1}; however, afterward, plant height did not change (Fig. 2A). A similar trend was observed during both growing seasons. Our data indicated that N application significantly affected the no. of tillers, no. of fertile tillers, and spike length (Fig. 2B-D). By increasing nitrogen levels from 0-150 kg ha^{-1}, the number of tillers, the number of fertile tillers, and spike length were significantly increased. However, high N doses (200-250 kg ha^{-1}) decreased the values for these yield components. A similar trend was observed during both years.

Table 1. Summary of the analysis of variance (ANOVA) for various attributes as affected by nitrogen levels and year interactions.

Source of variation	Treatment	Treatment x Year
Degree of freedom	5	5
Plant height	*	NS
Number of tillers	*	NS
Number of fertile tillers	*	NS
Spike length	*	NS
Number of grains per spike	*	NS
1000 Grain weight	*	NS
Grain yield	*	*
Biological yield	*	*
Harvest Index	*	NS
Flag leaf nitrogen concentration	*	NS
Grain nitrogen concentration	*	NS
Partial factor productivity (PFP)	*	*
Agronomic efficiency for nitrogen (AEN)	*	*
Internal efficiency for nitrogen (IEN)	*	*
Partial nitrogen balance (PNB)	*	*
Recovery efficiency for nitrogen (REN)	*	*
Physiological efficiency for nitrogen (PEN)	*	*
Nutrient use efficiency (NUE)	*	*

Where, * indicates probability level significant at 0.05, and NS indicates non-significant.

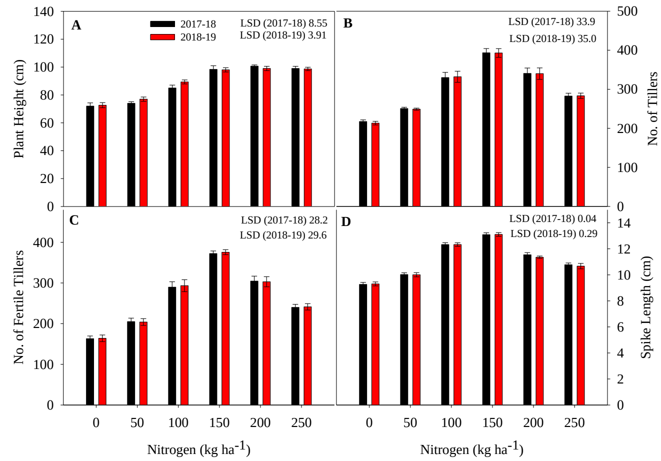

Figure 2. Effect of nitrogen treatments on plant height (A), no. of tillers (B), no. of fertile tillers (C), and spike length (D). Bars are means of three replicates ± SE.

***Leaf and grain N concentration*:** According to statistical data, 100 kg N ha^{-1} significantly affected flag leaf N concentration. By increasing the nitrogen fertilizer rate from 0-200 kg ha^{-1}, flag leaf nitrogen concentration was also gradually increased (Fig. 3A). Statistical data indicates that nitrogen application at the rate of 100 kg ha^{-1} significantly affected grain nitrogen concentration. Grain nitrogen concentration increased gradually by applying nitrogen from 0-150 kg ha^{-1} and slightly decreased at higher nitrogen doses (200-250 kg ha^{-1}) (Fig. 3B).

Analyzed data also indicated that grains per spike were increased gradually from 0 to 100 kg ha^{-1} in the first year of experimentation (2017-18) and then showed a slight decline at higher doses (200-250 kg ha^{-1}). During the second year (2018-19), the grains per spike significantly improved up to 200 kg ha^{-1} and declined afterward (Fig. 3A). Thousand-grain weight was maximum at 150 kg ha^{-1}, while higher N application rates (200 and 250 kg ha^{-1}) decreased the thousand-grain weight in both years compared to 150 kg ha^{-1} (Fig. 3B). Analyzed data showed that the control treatment showed the lowest grain yield while increasing gradually when N application was applied at the 100-150 kg ha-1 rate. Afterward, the grain yield slightly declined at higher nitrogen fertilizer rates, i.e., 200-250 kg ha^{-1} (Fig. 3C). The biological yield of wheat was significantly improved by applying N fertilizer gradually from 0-250 kg ha^{-1} during both years (Fig. 3D). The harvest index of wheat gradually increased from 0-100 kg ha^{-1} and then decreased gradually when the dose of N fertilizer was increased (Fig. 3E).

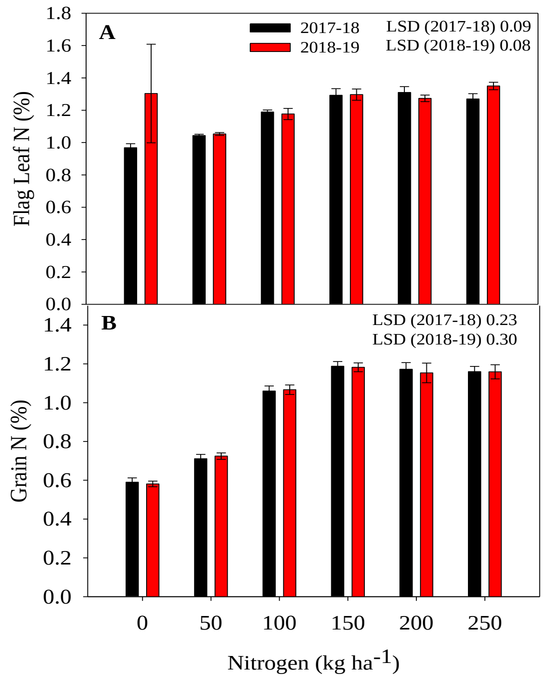

Figure 3. Effect of nitrogen treatments on flag leaf (A) and grain (B) nitrogen concentration. Bars are means of three replicates ± SE.

***NUE indices*:** An increase in nitrogen application decreased PFP, showing an indirect relation. PFP was highest at 50 kg ha$^{-1,}$ decreased gradually by increasing nitrogen levels, and showed the lowest PFP at 250 kg ha^{-1}. Both years showed similar results (Fig. 4A). Experimental results showed that the value of AEN was highest at 100 kg ha^{-1}. During the second year (2018-19), the AEN was significantly higher than the first crop season (2017-18). When the N dose was increased, the value of AEN declined gradually. The lowest value of AEN was observed at 250 kg ha^{-1} (Fig. 4B). Results show a similar trend during both years.

The data for both years showed a similar trend. The results showed that IEN was maximum at the lowest application rate of 50 kg ha^{-1}. With an increase in nitrogen rates (100-150 kg ha^{-1}), the IEN gradually decreased and remained constant at 200-250 kg ha^{-1} (Fig. 4C). An indirect relation exists between nitrogen fertilizer rates and PNB. By increasing nitrogen levels, the value of PNB decreased gradually. The maximum PNB was observed at 100 kg ha^{-1} (Fig. 4D). The REN significantly increased to 100 kg ha^{-1} and then declined with an increase in N rates**.** The REN was lowest at the rate of 250 kg ha^{-1} (Fig. 4E). A similar response was observed for REN during both years; however, the REN values in response to all N levels were significantly higher during the year 2018-19 as compared to 2017-18.

Table 2. Pearson's correlation among selected variables during 2017 and 2018. The coefficients among variables were determined across different N fertilizer rates. Asterisks denote significant differences. *<0.05; **<0.01; *<0.001.**

	IEN	NUE	PEN	PFP	PNB	REN	GY	GN	TGW
					2017-18				
AEN	-0.11	0.85***	0.04	0.38	0.66**	0.93***	0.31	0.61*	0.75**
IEN		0.36	0.96***	0.84***	0.60	-0.43	-0.94***	-0.62*	-0.57*
NUE			0.47	0.79***	0.95***	0.67**	-0.16	0.26	0.42
PEN				0.87***	0.66**	-0.29	-0.88***	-0.53*	-0.46
PFP					0.93***	0.09	-0.71**	-0.27	-0.12
PNB						0.43	-0.42	0.01	0.21
REN							0.60*	0.76***	0.89***
GY								0.6**	0.69**
GN									0.71**
					2018-19				
AEN	0.31	0.93***	0.44	0.68**	0.88***	0.78***	0.23	-0.04	0.41
IEN		0.51	0.95***	0.87***	0.51	-0.29	-0.80***	-0.79***	-0.57*
NUE			0.55*	0.85***	0.98***	0.66***	-0.04	-0.27	0.27
PEN				0.85***	0.52*	-0.18	-0.64**	-0.65**	-0.49
PFP					0.86***	0.18	-0.5418	-0.65**	-0.202
PNB						0.64**	-0.11	-0.32	0.26
REN							0.66**	0.39	0.82***
GY								0.84***	0.80***
GN									0.64**

Note: Agronomic efficiency for nitrogen (AEN), internal efficiency of nitrogen (IEN), nitrogen use efficiency (NUE), physiological efficiency for nitrogen (PEN), partial factor productivity (PFP), partial nitrogen balance (PNB), recovery efficiency for nitrogen (REN), grain yield (GY), number of grains per spike (GN), thousand-grain weight (TGW).

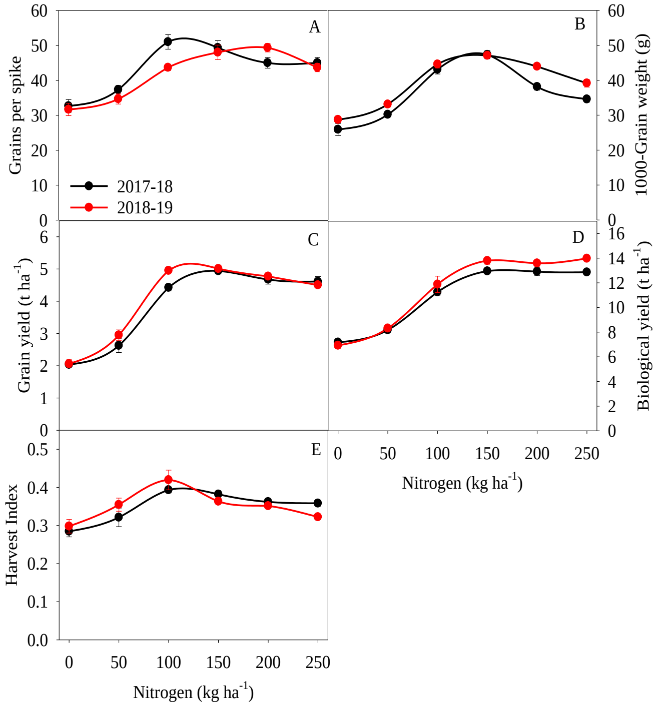

Figure 4. Effect of nitrogen treatments on the number of grains per spike (A), 1000-grain weight (B), grain yield (C), biological yield (D), and harvest index (E). Values are means of three replicates ± SE.

The PEN was also decreased with an increase in nitrogen application. We found that the PEN was maximum at 50 kg N ha^{-1} and minimum at 250 kg N ha^{-1} (Fig. 4F). The NUE was greatly influenced by nitrogen fertilization. The data showed that NUE increased when nitrogen was applied from 50-100 kg ha^{-1} and decreased with a further increase in N application rates. The highest value of NUE was observed at 100 kg N ha$^{-1,}$ and the lowest NUE was recorded at 250 kg N ha^{-1} (Fig. 4G). Although the trend for NUE response to N application rates was similar during both years, 2018-19 recorded significantly higher NUE than 2017-18.

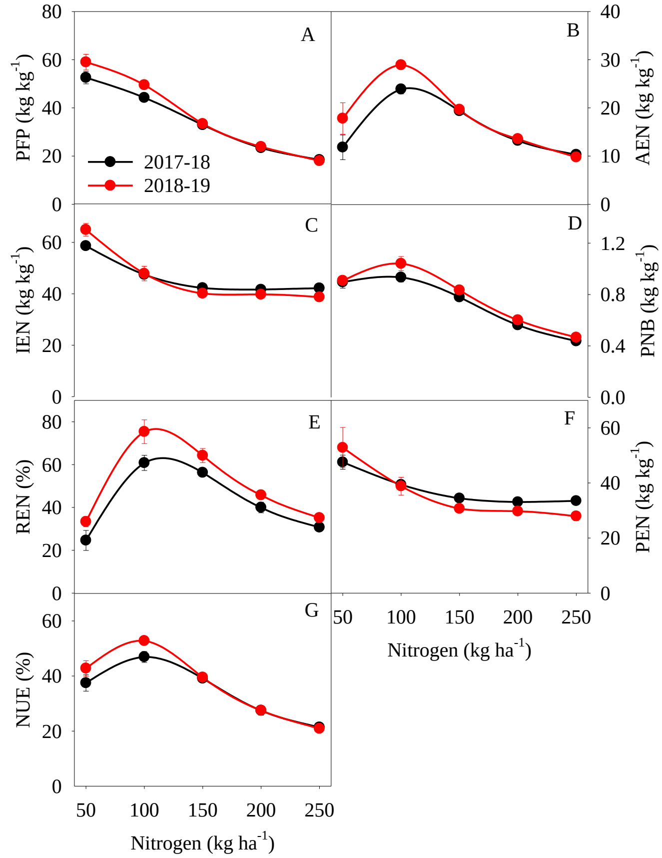

Figure 4. Effect of nitrogen treatments on partial factor productivity (PFP; A), agronomic efficiency of nitrogen (AEN; B), internal efficiency of nitrogen (IEN; C), partial nitrogen balance (PNB; D), the recovery efficiency of nitrogen (REN; E), physiological efficiency of nitrogen (PEN; F) and nitrogen use efficiency (NUE; G). Values are means of three replicates ± SE.

Correlation analysis: The GY was positively and significantly correlated with GN, TGW, and REN during both study years (Table 2). The GY also positively correlated with

Table 3. Economic analysis and benefit-cost ratio of nitrogen fertilizer treatments. Currency conversion rates are as of 23 June 2022 (1 USD = 210 PKR).

N Levels kg ha^{-1}	2017-18				2017-18			
	Total expenditure	Gross income	Net income	Benefit-cost ratio	Total expenditure	Gross income	Net income	Benefit-cost ratio
	(USD/ha)							
0	1015	714	-300	0.70	1015	715	-300	0.70
50	1035	895	-140	0.86	1035	985	-51	0.95
100	1056	1447	391	1.37	1056	1602	546	1.52
150	1076	1625	549	1.51	1076	1664	588	1.55
200	1097	1554	458	1.42	1097	1597	500	1.46
250	1117	1536	418	1.37	1117	1534	417	1.37

AEN, though the relationship was insignificant. Similarly, GN has a significantly positive correlation with AEN and REN during 2017-18. However, GN positively correlated with REN during 2018-19, though the results were insignificant. Grain weight also has a significantly positive correlation with REN during both years. While the relationship between TGW and AEN was positive during both years, it was statistically significant only during 2017-18. Concerning the relationship of NUE indices with grain yield and yield components, IEN, PFP, and PEN have a negative correlation with GY, GN, and TGW during both years.

***Cost-benefit ratio*:** The economic analysis compared the nitrogen treatments for their total expenses, gross income, and net profit. The results showed that an increase in N application rates gradually increased the benefit-cost ratio (BCR) to 150 kg ha^{-1} during both years (Table 3). However, an additional increase in N application rates (200-250 kg ha^{-1}) reduced the BCR. A similar trend was observed during both years.

DISCUSSION

Pakistan is one of the developing countries which is struggling with food insecurity and climate change catastrophes at the same time. Overuse of nitrogenous fertilizers is one of the major contributors to greenhouse gas emissions. Since the 1960s, the nitrogen application rates for major crops, including wheat are continuously rising in Pakistan (Shahzad *et al.*, 2019). On the other hand, the mean wheat yields have been almost stagnant for the past two decades resulting in a constant declining trend of nitrogen use efficiencies (NUE). The low NUE indicates a high production cost and high N losses to the environment. Though multiple factors could be responsible for low mean yields in Pakistan, imbalanced fertilization and N overuse are the main contributors. Considering the above, this study aimed to optimize the N fertilizer rates towards a maximum attainable yield potential of wheat and a high NUE under the agro-climatic conditions of Multan.

Plant height refers to an overall increase in vegetative growth. Results showed that N application increased plant height to a specific dose, and afterward, N overdose had a slightly negative impact. The number of tillers and the number of fertile tillers are the main components of wheat yield. Experimental data showed these variables were improved by nitrogen application, and overdose had a negative impact. Optimum nitrogen improves the number of grains per spike and thousand-grain weight. We found that grains per spike and grain weight were increased up to 150 kg N $ha^{-1;}$ however, higher doses negatively affected the attributes. Grain yield increased to a certain nitrogen level (150 kg N ha^{-1}); however, excessive nitrogen harmed grain yield (Rutting *et al.,* 2018; Kartseva *et al.,* 2021).

Our results show that overusing nitrogen fertilizer (200 and 200 kg N ha^{-1}) negatively influenced the grain yield and components. The inhibitory effect of excessive N could be due to an impaired antioxidant defense system and disruption in metabolic activities that lead to poor grain filling and reduced grain yields (Kong *et al*., 2017). Liu *et al*. (2021) observed that excessive N reduces the grain filling rate by inhibiting the assimilate transport via a change in hormone balance. At high N application rates, other essential minerals, particularly potassium, can also be depleted, which may also cause a decline in grain yield and components (Hamner *et al*., 2017). Our results show that a wheat grain yield of 5 t ha^{-1} can be achieved with 150 kg N ha^{-1}. However, the current cultivation practices only produce 2.9 t ha^{-1} mean wheat yields at N input rates of more than 200 kg N ha^{-1} in Pakistan (Shahzad *et al*., 2019). The Department of Agriculture recommends 158 kg N ha^{-1} (2022-23) for low-fertility soils, which is not tailored to the yield potential of these soils as it does not consider the other yield-limiting factors. Resultantly, in the high-input low-output environment of the country, N is overused, which causes very low NUE. Our results suggest that farmers in Pakistan should only use 150 kg N ha^{-1}, if the agronomic yield potential is 5 t ha^{-1} and other agronomic factors like balanced fertilization, irrigation, etc, are not limiting.

The partial factor productivity (PFP) for nitrogen, described as crop yield per unit of nitrogen applied, is a practice to compare the economic returns of fertilization. It is influenced by fertilizer dose, method and form, soil quality, yield potential, and management practices (Dobermann, 2005). The value of the average PFP is 44 kg grain per kg nitrogen in the world (Dobermann and Cassman, 2005). According to Dobermann (2005), the ideal PFP for nitrogen can range from 40-70 kg grain per kg nitrogen. However, it could be more than 70 kg kg^{-1} in case of a low dose of nitrogen or a well-managed system. In our experiment, 100 kg N ha^{-1} produced the maximum PFPs of 44.23 and 49.5 kg kg^{-1} during 2017-18 and 2018-19, respectively. While higher N application rates (150-250 kg N ha^{-1}) significantly reduced the PFPs. The agronomic efficiency of nitrogen (AEN) is an increase in grain yield per unit of nitrogen applied. The average AEN for wheat can range from 20-25 kg grain per kg N around the world (Hooper, 2010). AEN of 10-30 kg/kg is found at low N doses, while it may increase from 30 kg/kg under optimum nutrient management (Dobermann, 2007). Our study recorded maximum AENs of 23.8 and 28 kg/kg at fertilizer application rates of 100 kg ha^{-1} in 2017-18 and 2018-19, respectively. While higher fertilizer rates substantially reduced the AEN. Increasing the N level, AEN declined (Arduini *et al.*, 2006) due to higher N losses.

The partial nitrogen balance (PNB) is the ratio of N removal to N use. According to Snyder and Bruulsema (2007), PNB should be >1 for nitrogen deficit soils, <1 for nitrogen surplus soils, and near 1 for sustainable soils. Our results showed that 100 kg ha^{-1} showed maximum PNBs of 0.933 kg/kg in the first year (2017-18) and 1.04 kg/kg in the second (2018-19) year. Internal use efficiency of nitrogen (IEN) refers to the capability of the crop to convert nitrogen into grain yield (Liu *et al.*, 2011). When the value of IEN is too high, it indicates a deficiency of nitrogen and vice versa (Dobermann and Cassman, 2005). The IEN was decreased with increasing nitrogen levels. The value of IEN for cereal ranges from 18.3–65.9 kg/kg (Pathak *et al.*, 2003). The ideal IEN for nitrogen should be 55 to 65 kg/kg for balanced nutrient soil (Dobermann, 2007). In our study, IEN was maximum at 50 kg N ha^{-1} with 58.63 kg/kg in the first year (2017-18) and 64.9 kg/kg in the second year (2018-19).

The recovery efficiency for nitrogen (REN) is the difference between nitrogen uptake and nitrogen application. For wheat, the average REN was 57% in a review of global data (Ladha *et al.*, 2005). The REN should be 50-80% for well-managed soils and 30-50% for low-nitrogen soils (Dobermann, 2007). Our results showed maximum REN at 100 kg N ha^{-1} with a value of 60.7% during the first year and 75.3% during the second year. Further increase in N application reduced the REN. At low nitrogen application rates, crop recovery of N is more efficient than at higher doses (Nabin *et al.,* 2022). Physiological efficiency of nitrogen (PEN) refers to the yield increase per unit of applied nitrogen. PEN should be >60 kg/kg in well-managed soils and 30-60 kg/kg for average soils or low nitrogen supply (Dobermann, 2005). In our findings, PEN is highest at 50 kg N $ha^{-1,}$ with 47.5% during 2017-18 and 52.8% during 2018-19. More nitrogen applications showed negative results. PEN is highest at low nitrogen supply and vice versa (Belete *et al.,* 2018; Mojid *et al.,* 2012). Nitrogen use efficiency (NUE) in our experiment is maximum at 100 kg N ha-1 nitrogen application with 46.9% in the first year of study and 52.7% in the second year.

The positive relationships of grain yield and yield components with AEN and REN agree with other studies (Fageria, 2009; Boulelouah et al., 2022). These studies indicated that the positive relationship between GY and AEN could be an indirect effect of REN, and these relationships are dependent on soil N mineralization.

***Conclusion*:** Optimum use of nitrogen fertilizers is vital in enhancing crop production, profitability, and improving the NUE. It is a severe issue in Pakistan and world agriculture to minimize inputs and improve yields with low environmental hazards. The findings of this study show that N application at 150 kg ha^{-1} produced the maximum grain yield and cost-benefit ratio. However, higher doses of N application increased the biological yield but harmed grain yield and related components. While nitrogen efficiency indices revealed that wheat produced the best nitrogen use efficiency at 100 kg N ha^{-1}. Since the benefit-cost ratio was almost comparable at 100 and 150 kg N ha^{-1}, it is recommended that 100-150 kg N ha^{-1} should be used if the expected yield is 5 t ha^{-1}. While if other factors limit the yield, farmers can get the best output at 100 kg N ha^{-1}. These findings may apply to other regions of Pakistan with similar climates, soil, and cropping systems.

***Author Contribution*:** ANS& NH designed the study, TM conducted the study and collected the data, SAHB analyzed the data, SS, ANS & MKQ wrote the manuscript.

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