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Nitrogen Use Efficiency in Durum Wheat (*Triticum durum* Desf.) Grown under Semiarid Conditions in Algeria

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Abstract: The proper and sustainable management of nitrogen fertilization is one of the most common problems of cereal cultivation in semiarid regions, which are characterized by a wide variability in climatic conditions. The current work was conducted to evaluate the effects of nitrogen fertilization on the agronomic and economic aspects of durum wheat cultivated under rainfed semiarid conditions in Algeria and to determine the most efficient nitrogen use efficiency (NUE) among four genotypes that are widespread in the country (tall and short, old and modern genotypes). The four genotypes, Bousselam, MBB, Megress, and GTAdur, were investigated under four nitrogen rates from 0 to 120 kg N ha^{-1} during three cropping seasons (2016 to 2018). The results indicate that the total nitrogen uptake at maturity (NM), nitrogen uptake by grain (NG), nitrogen harvest index (NHI), NUE and its components, such as nitrogen uptake efficiency (NUpE) and nitrogen utilization efficiency (NUtE), were significantly affected by year, genotype, and nitrogen level. From this study, it appears that higher nitrogen rates improved NM and NG. However, no effects on either grain yield or marginal net return (MNR) were observed; conversely, increased nitrogen levels produced a 13% reduction in the economic return. In other words, in the North African environment, the response to nitrogen is more evident in quality than in yield, which in turn is dependent on the yearly weather conditions and cultivated genotypes. Moreover, nitrogen negatively affected NUE and its components (NUpE, NUtE). On average, NUE displayed low values (14.77 kg kg^{-1}), mostly irregular and highly dependent on weather conditions; in the best year, it did not exceed 60% (19.87 kg kg^{-1}) of the global average value of 33 kg kg^{-1}. Moreover, the modern genotypes Megress (tall) and GTAdur (short) showed the best capacity to tolerate different nitrogen conditions and water shortages, providing relatively superior yields, as well as more effective N use from fertilizers and the soil than the other two genotypes.

Keywords: durum wheat; nitrogen fertilization; nitrogen use efficiency; NUpE; NUtE; marginal net return (MNR)

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1. Introduction

Durum and common wheat constitute the backbones of the Algerian food system and industry [1]. Durum wheat (*Triticum durum* Desf.) is the first and economically major crop in Algeria; it represents 46% of total cereal production, cultivated on 1.6 million hectares, with a variable average production ranging between 1.3 and 3.1 million t [2,3]. However, the durum wheat produced covers only 24% to 55% of the annual consumption of the country, which is around 202 kg capita^{-1} year^{-1} [3,4], while the rest is mainly ensured by imports, to satisfy the rising needs, which makes Algeria the world's leading importer of durum wheat (50% of world trade) [4]. This situation is explained by the Algerian diet, mainly based on the consumption of durum wheat in its various forms (couscous, pasta, bread, freekeh, baghrir, tamina, makrout, aich, braj, cherchem, rechta, etc.) and on the low yields obtained in the country. All these dishes require a material with high quality. However, the manufacturers in Algeria judge the quality of durum wheat to be average to mediocre (low grain protein content and low vitreosity) [5].

In Algeria, the durum and common wheat yield is only 50% of the world average, in the best years—namely, on average, 1.42 t ha^{-1} (2000–2018) [6]. This weakness is mainly due to the effect of the dry climate that often occurs during the crop cycle (insufficient and erratic rainfall, low winter temperatures, spring frosts, drought in the late-season, and sirocco occurrence) [7–9], combined with the more recent effects of climate change [10], which are forcing farmers to adopt extensive cropping systems in rainfed farming areas [4] with poor control of the agricultural technical itinerary [11]. The main challenge under these climatic conditions is to achieve the best grain yield with high quality by the optimization of nitrogen (N) fertilization and the choice of variety [12].

N fertilization is among the inputs that has strongly increased globally in the last decades because it constitutes, after water, one of the improvement factors of grain yield and quality [13,14]. However, at the same time, economic and environmental negative effects can be observed if N fertilization is not efficiently managed [15–18]. Many studies have clearly demonstrated that N uptake and N remobilization are strongly affected by the N supply [19–21]. However, the response to N fertilizer is variable, due to genotype, environmental conditions, and their interactions, which include the contribution from N available in the soil. Moreover, many studies showed that the overuse of N fertilizer induced a decrease in NUE in bread wheat [22–27], but few studies are available on durum wheat [12]. This problem is more and more accentuated in semiarid regions, where the availability of soil water is the principal factor limiting the yield capacity and its response to N fertilizers. Indeed, some authors [22,28] reported that in semiarid regions characterized by a rainfall shortage, the response of wheat to N fertilization was low or nonexistent, and the N input is not always justified, in particular due to the intra-and interannual rainfall fluctuations. In fact, in the case of early rain, a high N supply can induce an early growth of plants and a consequent increased tillering that causes a rapid depletion of water in the soil, and a low grain yield might be expected if rainfall conditions are in deficit during the grain filling period [29]. Moreover, if the water deficit continues throughout the growth season, the N uptake is lower or even stopped, and N fertilizer negatively impacts the environmental and economic farm sustainability [30,31]. Conceptually, NUE is the efficiency ratio of output (economic yield) to input due to N fertilizers. In Moll et al. [31], NUE is defined as the grain yield per unit of available N (soil + N fertilizer or as N fertilizer). They also proposed that NUE can be partitioned into the components of N uptake efficiency (NUpE, plant N per unit of either soil + N fertilizer or only N fertilizer) and N utilization efficiency (NUtE, grain yield per unit of N in the plant); the product of these two components results in NUE. The relative contribution of NUpE and NUtE to the NUE depends, among other things, on the species, N availability in the soil, and how plants use N throughout their lifespan [22,32]. The NUE of worldwide cereal crops was estimated to be near 33% [33], ranging from 14% to 59% in wheat [21,34,35]. In addition, the efficiency of N fertilizer in Mediterranean climates was lower than that observed in temperate areas [28]. To overcome this situation, it is necessary to reduce the N fertilizers applied in these areas and to select genotypes that are able to use N better and have a higher NUE, thus improving the economic efficiency of the crop and reducing the negative agricultural impacts on air and water due to nitrate leaching and volatilization, while, at the same time, preserving the environment and improving sustainable and productive agriculture [15,27,32,36–38]. Furthermore, in semiarid conditions the response of tall or short genotypes and old or modern ones to N fertilization is not well elucidated. From these premises, we hypothesized that intraspecific variation is one of the keys to improving the NUE under semi-arid conditions. Consequently, the objectives of our study were (1) to fill the knowledge gap on NUE in durum wheat under semiarid conditions and (2) to evaluate the effects of N rates on the agronomic and economic aspects of the most widespread Algerian durum wheat genotypes determining the most efficient in terms of N use efficiency (NUE) among four genotypes widespread in the country.

2. Materials and Methods

2.1. Site Description and Crop Management

The experiment was conducted during three cropping seasons (2015/16, 2016/17, and 2017/18) at the experimental Algerian Field Crop Institute of Sétif-Algéria (ITGC). The geographical coordinates of the site are reported in Table 1. The climate of the region is typically subject to semiarid conditions. Figure 1 shows the monthly air temperatures and precipitation during the three growing seasons. For the soil, it is predominantly clay; the rate of limestone is high, with an alkaline pH of 8. The risk of salinity is low as well as the organic matter and the soil fertility of elements (N, P, and K). The soil chemical and physical properties are reported in Table 1. The previous crop was fallow in the first and second years and wheat in the third one. Sowing, fertilization, and harvest dates were adapted to climatic conditions or plant development stages during each year (Table 1).

Table 1. Experimental details and dates of the main phenological stages during the three cropping seasons (in separate columns).

		Properties of Experimental Site	
Coordinates		36°08′ N, 5°20′ E.	
Altitude (m)		962 m a.s.l.	
Soil texture		Clay soil (Sand 40%, Silt 4%, Clay 56%)	
pH (in H_2O)		8.29	
Electrical conductivity (mS/cm)		0.22	
Organic matter (%)		1.88	
C/N ratio		7.81	
Total N (%)		0.14	
Available Phosphorus P (ppm)		29.8	
Exchangeable potassium K (meq/100 g)		1.3	
Harvest year	2015–2016	2016–2017	2017–2018
Sowing date	3 December 2015	22 December 2016	2 January 2018
The first N supply at beginning of tillering	1 February 2016	1 March 2017	17 March 2018
The second N supply at beginning of stem elongation	4 April 2018	12 April 2017	19 April 2018
Flowering	12 May 2016	3 May 2017	13 May 2018
Harvesting	18 July 2016	22 June 2017	22 June 2018
Number of days to heading	162	134	133

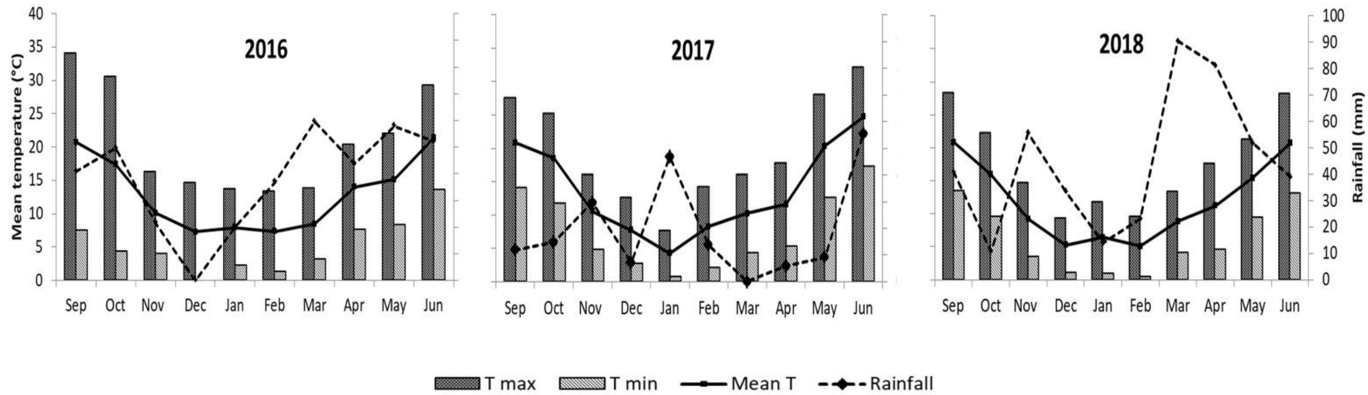


Figure 1. Monthly precipitation and minimum, maximum, and mean temperatures during the three cropping seasons (2016 = 2015/16; 2017 = 2016/17; and 2018 = 2017/18).

2.2. Experimental Design and Treatments Description

The trial was run under rainfed conditions, and it was arranged in a split-plot design with two factors: N level (N) and Genotype (G), and three repetitions. Each genotype was sown on a 6 row-plot, 2.5 m long, with 0.20 m row spacing. Seeds were sown at a density of 300 seeds m^{-2}. Four N rates were applied (N0 = 0, N1 = 40, N3 = 80, and N4 = 120 kg N ha^{-1}, where the total amount was split into 2 timings: the first one (1/3) at the beginning of tillering and the second one (2/3) at the beginning of stem elongation. N was applied as urea (46%). For the second studied factor, four varieties of durum wheat were used (Table 2), tall old: Mohamed Ben Bachir (MBB), tall modern: Megress, short old: Bousselam, and short modern: GTAdur. The chosen genotypes are widely grown in Algeria.

Table 2. Origin of the genotypes studied.

Genotypes	Pedigree	Origin
Bousselam	Heider/Martes//Huevos de Oro ICD86-0414-ABL-0TR-4AP-0TR-14AP-0TR	ICARDA-CIMMYT
MBB	Genealogical selection from a landrace population	ITGC (Setif)
Megres	Ofanto/Waha//MBB	ITGC (Setif)
GTAdur	Crane/4/PolonicumPI185309//T.glutin en/2 * Tc60/3/Gll	ICARDA-CIMMYT

2.3. Sampling Method, Measurements of Traits, and Data Collection

At anthesis and harvesting, 0.5 m of three adjacent central rows (an area of 0.3 m^2) from each plot were cut at ground level and separated into straw and spike. All samples were dried at 65 °C for 72 h to obtain dry weight. At harvesting, after estimating the spikes' dry matter, the spikes were threshed to recover the grain, which was dried for 72 h at 80 °C and weighed to estimate the grain yield and its components (Table 3). Finally, all samples were milled, and their total N concentration was determined with the Dumas combustion method (LECO FP-528). The NUE and its components were calculated according to [25,31,39,40]; for the economic aspects, the marginal net return (MNR) was calculated according to [41], (Table 3).

Table 3. Description of measured and calculated traits.

Trait	Description	Formula	Units
DMS-F	Dry matter of spikes at flowering		kg ha^{-1}
DMST-F	Dry matter of straw at flowering		kg ha^{-1}
DMF	Total dry matter at flowering	DMS-F + DMST-F	kg ha^{-1}
DMS-M	Dry matter of spikes at maturity		kg ha^{-1}
DMST-M	Dry matter of the straw at maturity		kg ha^{-1}
DMM	Total dry matter at maturity	DMS-M + DMST-M	kg ha^{-1}
GY	Grain yield		kg ha^{-1}
NbrS m^{-2}	Number of spikes m^{-2}		
TGW	Thousand grain weight		(g)
HI	Harvest index	GY DMM^{-1}	%
NG	Nitrogen uptake by grain		kg N ha^{-1}
NST-M	Nitrogen uptake by straw at maturity		kg N ha^{-1}
NM	Total nitrogen uptake at maturity	NST-M + NG	kg N ha^{-1}
NHI	Nitrogen harvest index	NG NM^{-1}	
NUE	Nitrogen use efficiency	GY N $supply^{-1}$	kg kg^{-1}
NUpE	Nitrogen uptake efficiency	NM N $supply^{-1}$	kg kg^{-1}
NUtE	Nitrogen utilization efficiency	GY NM^{-1}	kg kg^{-1}
MNR	Marginal net return	(Yield × Price) − (Nfertilization × Cost)	€ t^{-1}

2.4. Statistical Analysis

The collected data were statistically analyzed by the GLM model of SAS software version 9.1.3, (SAS Institute, Cary, NC). Treatment means were compared with the least significant difference (LSD) at the 0.05 probability level with Fisher's LSD test. The correlation analysis of the different variables was performed using the Pearson test.

3. Results

3.1. Dry Matter Accumulation

The results over the three years of experimentation indicated highly significant differences among genotypes (G) and years (Y) for all investigated parameters apart from DMF between genotypes. N level (N) affected total dry matter at flowering (DMF), number of spikes m^{-2} (NbrS m^{-2}), and thousand grain weight (TGW). Moreover, there were significant interactions between Y × G and N × G; however, the Y × G × N interaction was never significant (Table 4). The highest total dry matter production at maturity (DMM) was obtained in 2015/16 with an average of 8589.93 kg ha^{-1} against 2541.66 and 7708.33 kg ha^{-1} in 2016/17 and 2017/18, respectively. The effect of N level on total dry matter (DMM) was not significant (Table 4), even when the years were relatively rainy (2015/16 and 2017/18), except for the total dry matter at flowering (DMF) (Figure 2A), which was positively affected and increased on average by 11% compared to N0. This positive difference was essentially due to the increase in the number of spikes m^{-2} (15%), from 238 at N0 to 279 spikes m^{-2} at N3. The genotype effect indicated significant differences in the dry matter production capacity and its distribution between straw and spike. The short genotypes Bousselam and GTAdur exhibited the lowest total dry matter at maturity (DMM) with values of 5951.38 and 5985.18 kg ha^{-1}, respectively, compared to the tall ones MBB and Megress, which produced 6694.90 and 6488.42 kg ha^{-1}, respectively. The tall genotypes showed a positive response to the N level, and they increased the total dry matter (DMM) from N0 to N3 (Figure 2B).

Table 4. Means and ANOVA results of dry matter accumulated at flowering and maturity and grain yield and its components.

		DMF	DMM	GY	NbrS m^{-2}	TGW	HI	MNR
Effect Years (Y)	2015/16	6859.37	8589.93	2614.58	256.28	39.45	30.61	707.85
	2016/17	1917.36	2541.66	933.68	186.66	32.91	36.31	236.67
	2017/18	4316.66	7708.33	2747.22	325.55	41.45	35.79	745.03
Test F	*p*	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***
	LSD	351.44	456.01	193.39	18.318	1.238	2.269	55.2
Effect Nitrogen level (N)	0	4070.37	6230.55	2163.88	237.68	40.43	35.18	606.55
	40	4263.42	6150.00	2038.88	249.86	38.50	33.59	554.82
	80	4541.66	6330.55	2123.61	258.14	37.18	34.69	561.88
	120	4582.40	6408.79	2067.59	278.98	35.66	33.50	529.48
Test F	*p*	0.0441 *	0.7785 NS	0.6858 NS	0.0020 **	<0.0001 ***	0.5047 NS	0.1196 NS
	LSD	405.81	526.55	223.31	21.152	1.429	2.6201	63.739
Effect Genotype (G)	Bousselam	4205.55	5951.38	1893.51	290.74	36.62	33.12	505.73
	MBB	4572.68	6694.90	1931.01	235.83	37.19	29.66	516.24
	Megress	4518.98	6488.42	2396.29	256.20	42.50	37.76	646.66
	GTAdur	4160.64	5985.18	2173.14	241.89	35.45	36.42	584.11
Test F	*p*	0.1005 NS	0.0114 *	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***
	LSD	405.81	526.55	223.31	21.152	1.429	2.6201	63.739
Y × N	*p*	0.2042 NS	0.4485 NS	0.8751 NS	0.0427 *	0.0003 **	0.0846 NS	0.8846 NS
Y × G	*p*	0.0007 **	0.0012 **	0.0008 **	<0.0001 ***	<0.0001 ***	0.0970 NS	0.0011 **
G × N	*p*	0.0025 **	0.0026 **	0.0119 *	0.0356 *	0.4705 NS	0.2435 NS	0.0150 *
Y × G × N	*p*	0.0688 NS	0.7441 NS	0.3635 NS	0.1717 NS	0.1733 NS	0.7122 NS	0.4021 NS
	Means	4364.46	6279.97	2098.49	256.16	37.94	34.24	563.19
	CV%	19.86	17.91	22.73	17.64	8.05	16.35	24.18

DMF = Total dry matter at flowering (kg ha^{-1}), DMM = Total dry matter at maturity (kg ha^{-1}), GY = Grain yield (kg ha^{-1}), NbrS m^{-2} = Number of spikes m^{-2}, TGW = Thousand grain weight (g), HI = Harvest index (%), MNR = Marginal net return (euro t^{-1}), NS = no significant value, * = significant value at $p < 0.05$, ** = significant value at $p < 0.01$, *** = significant value at $p < 0.001$, CV% = Coefficient of variation, LSD = Least significant difference.

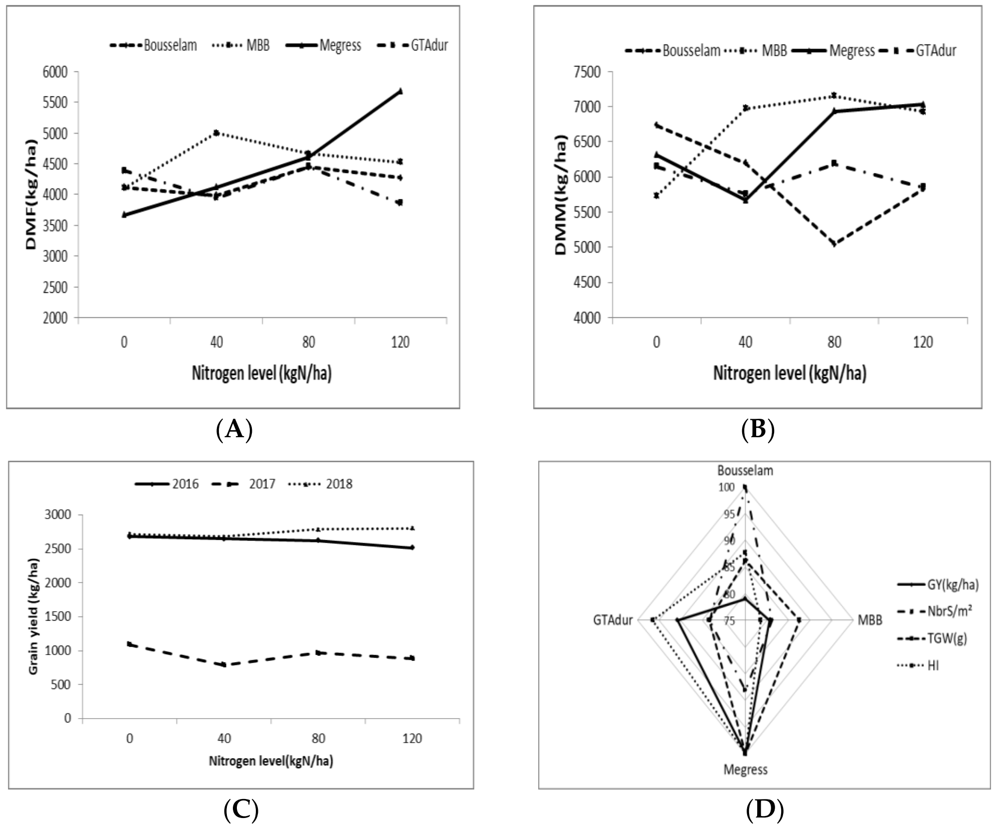


Figure 2. Nitrogen effect on dry matter at flowering (**A**) and maturity (**B**), grain yield (**C**), and genotype grain yield performance (**D**). DMF = Total dry matter at flowering (kg ha^{-1}), DMM = Total dry matter at maturity (kg ha^{-1}), GY = Grain yield (kg ha^{-1}), NbrS m^{-2} = Number of spikes m^{-2}, TGW = Thousand grain weight (g), HI = Harvest index (%).

3.2. Grain Yield and Yield Components

The grain yield was similar during seasons 2015/16 and 2017/18 and significantly lower in 2016/17. The highest values of grain yield (2747.22 kg ha^{-1}), NbrS m^{-2} (325.55), TGW (41.45 g), and HI (35.79%) were in the third year (2017/18). On the other hand, during the driest year (2016/17), grain yield decreased by 65.18% from the average of the other two years (Figure 2C). The response of grain yield to the increasing N level was not significant. However, the TGW was negatively affected by the N increase; TGW was significantly higher at N0 (40.43 g) than at N3 (35.66 g). As for the genotypes, they showed different capacities for the expression of yield and its components (Table 4, Figure 2D). The genotypes Megress and GTAdur gave the best yields with an average of 2396.29 kg ha^{-1} and 2173.14 kg ha^{-1}, respectively. The highest TGW was obtained by Megress with an average of 42.5 g and also the best distribution of dry matter between grain and straw with a higher HI of 37.76%. However, Bousselam showed the highest number of spikes m^{-2} with an average of 290.74 spikes m^{-2}.

3.3. Marginal Net Return (MNR)

The marginal net return (MNR) of N fertilization significantly differed between years and genotypes (Table 4); the highest value of MNR was obtained in the wet year of experimentation (2017/18) with an average of 745.03 € t^{-1}, and the lowest value was obtained in the dry year (2016/17), with a reduction of 68% in the profit. For the genotype effect, a cheaper management was shown for both genotypes Megress and GTAdur, and the highest values of MNR were observed with an average of 646.66 and 584.11 € t^{-1}, respectively, whereas the N effect was not significant; moreover, N produced an economic reduction of about 13% from N0 to N120 (from 606.55 to 529.48 € t^{-1}, Table 4).

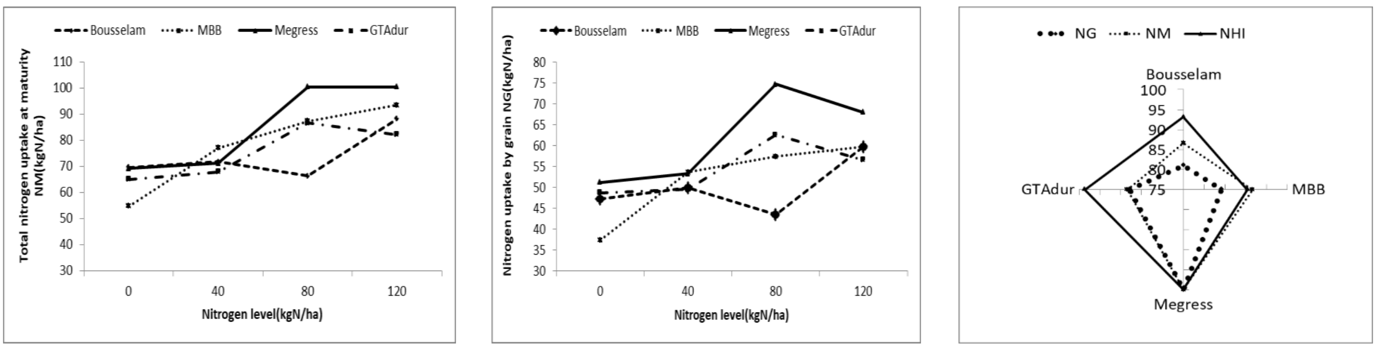
3.4. Total Nitrogen Uptake at Maturity, Nitrogen Uptake by Grain, and Nitrogen Harvest Index

The total N uptake at maturity (NM) significantly differed according to the year, N level, and genotype. Moreover, there were significant interactions between N × G and N × Y for NM (Table 5). The NM was proportional to the weather conditions of the cropping year; it was 110.10 kg N ha^{-1} in the wet year (2017/18) and much lower in the dry year: 33.62 kg N ha^{-1} in 2016/17, compared to 90.99 kg N ha^{-1} in 2015/16. In the three years, the NM significantly varied with the N level. It was always significantly greater when N fertilizer was applied compared to the unfertilized condition, and it increased from 64.68 kg N ha^{-1} at N0 to 91.08 kg N ha^{-1} at N3 (Figure 3A). The studied genotypes expressed different capacities to uptake N; Megress expressed the best capacity with an average value of 85.35 kg N ha^{-1}, followed by MBB, GTAdur, and Bousselam with an average value of 78.18, 75.44, and 73.96 kg N ha^{-1}, respectively (Figure 3A,C).

Table 5. Means and ANOVA results of NG, NM, NHI, NUE, and their components.

		NG	NM	NHI	NUE	NUpE	NUtE
Effect years	2015/16	60.37	90.99	0.66	19.87	0.74	26.11
(Y)	2016/17	24.92	33.62	0.73	7.95	0.29	27.34
	2017/18	78.32	110.10	0.70	16.50	0.68	24.07
Test F	*p*	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	0.0042 **
	LSD	5.3213	6.6924	0.0255	1.9662	0.0594	1.9105
Effect Nitrogen level	0	46.12	64.68	0.71	/	/	/
(N)	40	51.57	72.01	0.71	19.06	0.66	28.22
	80	59.51	85.17	0.70	14.35	0.57	25.30
	120	60.96	91.08	0.67	10.91	0.47	24.00
Test F	*p*	<0.0001 ***	<0.0001 ***	0.0221 *	<0.0001 ***	<0.0001 ***	0.0001 **
	LSD	6.1445	7.7277	0.0295	1.9662	0.0594	1.9105
Effect Genotype	Bousselam	50.05	73.96	0.68	12.67	0.50	24.73
(G)	MBB	52.00	78.18	0.66	15.02	0.54	27.66
	Megress	61.78	85.35	0.73	14.89	0.62	23.41
	GTAdur	54.32	75.44	0.72	16.51	0.60	27.55
Test F	*p*	0.0016 **	0.0216 *	<0.0001 ***	0.0129 *	0.0024 **	0.0002 **
	LSD	6.1445	7.7277	0.0295	2.2703	0.0686	2.2061
Y × N	*p*	0.0003 **	<0.0001 ***	0.1353 NS	0.0157 *	0.9928 NS	0.0003 **
Y × G	*p*	0.0081 **	0.0682 NS	0.0465 *	0.1050 NS	0.0103 *	0.6472 NS
G × N	*p*	0.0282 *	0.0167 *	0.6545 NS	0.0924 NS	0.1114 NS	0.8552 NS
Y × G × N	*p*	0.2388 NS	0.3935 NS	0.3526 NS	0.5432 NS	0.4855 NS	0.7195 NS
	Means	54.54	78.24	0.70	14.77	0.57	25.84
	CV%	24.07	21.10	8.94	28.30	22.05	15.72

NG = N uptake by grain (kg N ha^{-1}), NM = Total nitrogen uptake at maturity (kg N ha^{-1}), NHI = Nitrogen harvest index (%), NUE = Nitrogen use efficiency (kg kg^{-1}), NUpE = Nitrogen uptake efficiency (kg kg^{-1}), NUtE = Nitrogen utilization efficiency (kg kg^{-1}), NS = no significant value, * = significant value at $p < 0.05$, ** = significant value at $p < 0.01$, *** = significant value at $p < 0.001$, CV% = Coefficient of variation, LSD = Least significant difference.



(A) (B) (C)

Figure 3. Total nitrogen uptake by whole plant (**A**) and by grain (**B**) as affected by nitrogen level and genotype performance to uptake nitrogen (**C**). NG = N uptake by grain (kg N ha^{-1}), NM = Total nitrogen uptake at maturity (kg N ha^{-1}), NHI = Nitrogen harvest index (%).

The N uptake by grain (NG) depends on N remobilization from vegetative organs and N uptake after flowering [42]. Our results showed that the growing season, wheat genotype, and N level significantly affected the N uptake by grain (NG). Moreover, there were significant interactions between N × G, N × Y, and G × Y (Table 5). The NG was higher in the wet year 2017/18 (78.32 kg N ha^{-1}) and much lower during the dry year 2016/17 (24.92 kg N ha^{-1}) compared to 2015/16 (60.37 kg N ha^{-1}). The NG was as much affected by year, as by the significant interaction N × Y (Table 5). In the three years, NG was positively affected by the N increase. It was significantly higher at N3 compared to the unfertilized conditions (N0) with an increase of 24.35% (Figure 3B). The studied genotypes expressed different capacities to uptake N by the grains. Megress expressed the best capacity with an average value of 61.78 kg N ha^{-1}, followed by GTAdur, MBB, and Bousselam with respective values of 54.32, 52.00, and 50.05 kg Nha^{-1} (Figure 3B,C).

The N harvest index (NHI) represents the crop's ability to partition the total N uptake between the different plant organs [43]. The results showed that NHI varied significantly between years, N level, and genotypes (Table 5). The highest NHI was obtained in the dry year 2016/17 with an average value of 0.66, 0.73, and 0.70 recorded in 2015/16, 2016/17, and 2017/18, respectively. However, with an increasing N level, the overall NHI decreased from 0.71 at N0 to 0.67 at N3. As for the role of genotypes, NHI differed between 0.73 (Megress), 0.72 (GTAdur), 0.68 (Bousselam), and 0.66 (MBB).

3.5. Nitrogen Use Efficiency and Its Components

NUE is expressed as the kg of yield harvested per kg of N fertilizer applied. According to [32,44], it is the efficiency ratio of output (total plant N, grain N, biomass yield, and grain yield) to input (total N, soil N, or N-fertilizer applied). The NUE was mostly influenced by the cropping year (Table 5, Figure 4D). The average NUE was 19.87, 7.95, and 16.50 (kg kg^{-1}) in 2015/16, 2016/17, and 2017/18, respectively. As expected, NUE was negatively affected by the increase in N fertilization rate (Table 5, Figure 4A). It was significantly higher at N1 (19.06 kg kg^{-1}) than at N2 (14.35 kg kg^{-1}) and at N3 (10.91 kg kg^{-1}). In the present study, NUE values at N3 were 43% lower than those obtained at N1. However, the decrease was less marked in 2015/16 (52%) vs. 55% in 2016/17 and 65% in 2017/18, as shown by the trend in the interaction N × Y. As for the genotypes, the results showed that they expressed different abilities in NUE; the genotype GTAdur was more N efficient, with an average of 16.51 kg kg^{-1}, than MBB (15.02 kg kg^{-1}), Megress (14.89 kg kg^{-1}), and Bousselam (12.67 kg kg^{-1}) (Figure 4E).

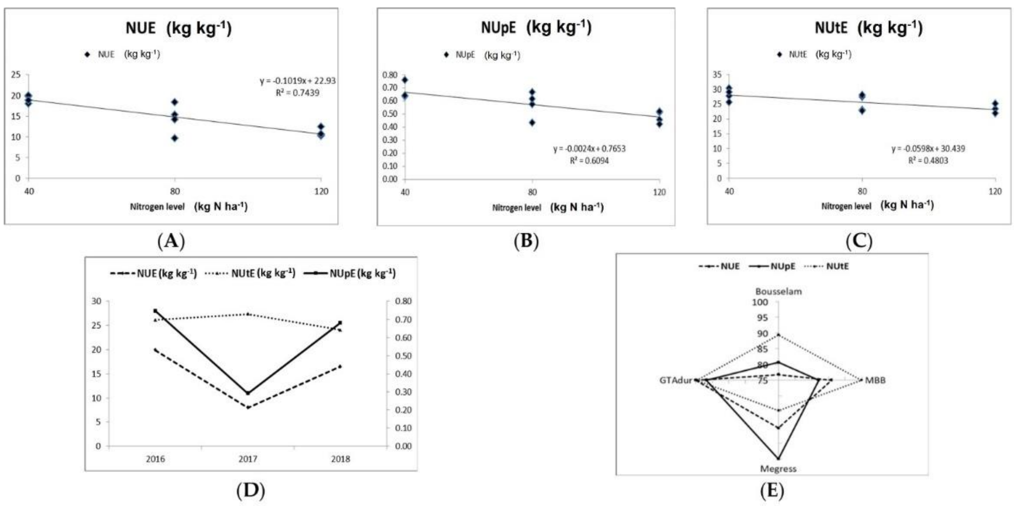


Figure 4. NUE (**A**) and its components NUpE (**B**) and NUtE (**C**), as affected by nitrogen level and by growing season (**D**) and the genotype performance for NUE and its components (**E**).

NUpE is the ability of the plant to remove N (as ammonium or nitrate ions) from the soil. According to [18], it widely depends on the cropping systems and N application strategies (timing, splitting, and forms of N used). The results showed that the wheat NUpE differed significantly between years, N levels, and genotypes. Moreover, there was a significant interaction Y × G (Table 5). As the average of N levels and genotypes, NUpE was 0.74 kg kg^{-1} in the less rainy first year 2015/16, 0.68 kg kg^{-1} in the rainiest third year 2017/18, and showed a very low value in the dry year 2016/17 (0.29 kg kg^{-1}). However, NUpE decreased with the increase in N level (Table 5, Figure 4B). It was 0.66, 0.57, and 0.47 kg kg^{1} for N1, N2, and N3, respectively. In the three years, the tall genotypes MBB and Megresse had higher NUpE values (0.54 and 0.62 kg kg^{-1}, respectively) than the short ones Bousselam and GTAdur (0.50 and 0.60 kg kg^{-1}, respectively) (Figure 4E).

NUtE is a parameter expressing the ability of the plant to translate the uptake N into economic yield (grains) [23]. The results showed that the wheat NUtE differed significantly between years, N levels, and genotypes. Moreover, there was a significant interaction Y × N (Table 5). NUtE was highly influenced by the cropping year, most likely by the yearly amount of rain; the highest value was registered in the dry year 2016/17 with an average value of 27.34 kg kg^{-1}; the values of 26.11 kg kg^{-1} and 24.07 kg kg^{-1} were in turn registered in 2015/16 and in the more rainy 2017/18, respectively. Moreover, the results showed that NUtE decreased with the increasing N level (Table 5, Figure 4C), with values of 28.22, 25.30, and 24.00 kg kg^{-1} at N1, N2, and N3, respectively. In the three years, the results showed that the genotypes expressed different abilities in NUtE, with MBB and GTAdur having a more efficient translocation of N from the plant to the grain with an average value of 27.66 and 27.55 kg kg^{-1}, respectively, than Bousselam and Megress, with values of 24.73 and 23.41 kg kg^{-1}, respectively (Figure 4E).

3.6. Correlations between NUE and Its Components with Other Traits

To understand the relationships between the NUE, yield, and its components, correlation analysis was performed considering all the recorded traits (Table 6). The results of the correlations indicated that the NUE was significantly and positively related with GY (0.79 ***), DMM (0.71 ***), NG (0.64 ***), TGW (0.61 ***), and NM (0.59 ***).

Table 6. Relationships between NUE and its components with dry matter, grain yield, and its components.

	DMF	DMM	GY	NbrS/m^2	TGW	HI	NG	NM	NHI	NuE	NUpE	NUtE
DMF	1											
DMM	0.78 ***	1										
GY	0.61 ***	0.89 ***	1									
NbrS/m^2	0.45 ***	0.54 ***	0.45 ***	1								
TGW	0.35 ***	0.57 ***	0.69 ***	0.26 **	1							
HI	0.34 ***	0.24 **	0.17 *	0.23 **	0.28 **	1						
NG	0.51 ***	0.80 ***	0.90 ***	0.58 ***	0.54 ***	0.15 NS	1					
NM	0.59 ***	0.85 ***	0.86 ***	0.64 ***	0.48 ***	0.01 NS	0.97 ***	1				
NHI	0.39 ***	0.25 **	0.08 NS	0.28 **	0.26 ***	0.81 ***	0.03 NS	0.16 *	1			
NUE	0.53 ***	0.71 ***	0.79 ***	0.21 *	0.61 ***	0.11 NS	0.64 ***	0.59 ***	0.16 NS	1		
NUpE	0.65 ***	0.84 ***	0.84 ***	0.40 ***	0.60 ***	0.06 NS	0.78 ***	0.79 ***	0.07 NS	0.90 ***	1	
NUtE	0.16 NS	0.13 NS	0.07 NS	0.37 ***	0.220 *	0.54 ***	0.14 NS	0.29 **	0.75 ***	0.35 **	0.025 NS	1

DMF = Total dry matter at flowering (kg ha^{-1}), DMM = Total dry matter at maturity (kg ha^{-1}), GY = Grain yield (kg ha^{-1}), NbrS m^{-2} = Number of spikes m^{-2}, TGW = Thousand grain weight (g), HI = Harvest index (%), NG = N uptake by grain (kg N ha^{-1}), NM = Total nitrogen uptake at maturity (kg N ha^{-1}), NHI = Nitrogen harvest index (%), NUE = Nitrogen use efficiency (kg kg^{-1}), NUpE = Nitrogen uptake efficiency (kg kg^{-1}), NUtE = Nitrogen utilization efficiency (kg kg^{-1}). * = significant value at $p < 0.05$, ** = significant value at $p < 0.01$, *** = significant value at $p < 0.001$.

NUpE was significantly and positively related to GY (0.84 ***), DMM (0.84 ***), NM (0.79 ***), NG (0.78 ***), and TGW (0.60 ***).

NUtE was significantly and positively correlated to NHI (0.75 ***) and HI (0.54 ***); moreover, it was significantly and negatively related to NbrS m^{-2} (−0.37 ***), NM (−0.29 **), and TGW (−0.22 *), respectively.

4. Discussion

In the Mediterranean area, several studies have shown that N fertilization is an effective technique for improving bread wheat yield and quality. However, few studies have been carried out in semiarid environments on durum wheat. Hence, the objectives of this study were to fill the knowledge gap on NUE in durum wheat under semiarid conditions and to evaluate the effects of N rates on the agronomic and economic aspects of Algerian durum wheat genotypes, determining the most efficient in terms of N use.

4.1. Dry Matter, Grain Yield, and Total N Uptake

In the present study, in an Algerian semiarid environment, the response of wheat grain yield to N level was not significant and very dependent on the yearly weather conditions and on the cultivated genotypes. The experiments were performed in a semiarid region with low rainfall below 500 mm per year (over 21 years, the average annual rainfall was 359.3 mm). The total rainfall in the three experimental years was 382.3 mm, 195.12 mm, and 440.7 mm, in 2015/16, 2016/17, and 2017/18, respectively. Therefore, it is evident that 2016/17 was a much drier year. In addition, in that season, the rain was poorly distributed throughout the cycle; an excess of rains occurred during the vegetative phase, followed by a severe deficit at the flowering stage and during grain filling (Figure 1). Rainfall between emergence and anthesis (Jan–April) varied more appreciably between the years of cultivation, totaling 160.4 mm, 66.62 mm, and 208.8 mm in 2015/16, 2016/17, and 2017/18, respectively. Rainfall during grain filling was also different between the years, although less drastically, 110, 64.7, and 91 mm from the first to the third year. For both 2015/16 and 2017/18, rainfall in the period between emergence and anthesis and during grain filling was higher than the long-term average, while in the second year 2016/17 it was much lower than the long-term average. The mean monthly temperature was similar over the three years and similar to the long-term average, but wide fluctuations were observed, particularly in the last period of the growing season with temperatures lower than the long-term average in the first and last years, and higher in the second year (Figure 1).

Most likely the excess of rains during the vegetative phase (Jan–Feb) in the first year 2015/2016 coupled with increasing levels of N fertilization promoted overtillering and, as a result, an increase in total dry matter (8589.93 kg ha^{-1}), with a reduced number of fertile spikes m^{-2} (256.28). These aspects most likely caused the reduction in the soil moisture during the grain filling period, and this exposed the wheat plants to water deficit, coupled with poor grain filling (TGW = 39.45 g), low grain yield (2614.58 kg ha^{-1}), and low harvest index (30.61%). These effects of the driest year are evident when compared to the third cropping season 2017/18, which was characterized by a more adequate rainfall distribution during the vegetative phase, which assured a higher number of fertile spikes m^{-2} (325.55) and a higher harvest index (35.79%), with superior TGW (41.45 g) and GY (2747.22 kg ha^{-1}).

During the three years, for all genotypes, the average grain yield was rather stable, fluctuating only between 2000 and 2100 kg ha^{-1} at the different N levels, notwithstanding the significant variation in the fertilization amounts between treatments. Similar results were reported by López-Bellido et al. [45], who showed, from a long-term experiment, that the response of wheat to N fertilizer levels in drought years, with rainfall below 450 mm in the growing season, could be low or nonexistent. In contrary, Souissi et al. [46] showed a significant effect of N supply on grain yield under semi-arid conditions. The results of the marginal net return showed that the N supply did not have a significant impact on it and produced a reduction of 13% in the farmers' income when passing from N0 to N120, in agreement with other authors [22,47].

On the other hand, in this study, there was a positive response of total dry matter at flowering to the increasing N. This positive effect was mainly due to the positive response of the number of tillers m^{-2} (data not shown), whose consequence was a higher number of spikes m^{-2}. This result can be explained by the fact that the water deficit and the high temperatures that occurred during the period of elaboration of the grain number (spike fertilization) and grain weight components were more limiting factors than the N availability; as a result, yields remained low in general. This result is in agreement with those of other authors [48–52] who showed that the climatic conditions (temperatures and rainfalls) during the vegetative season played a key role in grain production.

However, for the genotypic variability, our results showed different responses. The modern genotypes, Megress and GTAdur, expressed better performances in terms of grain yield without supplemental N fertilization, and they maintained such performances throughout the years and under different conditions of N availability. We can explain this result as Megress and GTAdur are more modern and productive genotypes than the old ones (Bousselam and MBB). As a result, under semiarid conditions in Algeria, the water deficit and high temperatures during grain filling are more limiting factors than N availability; moreover, the modern genotypes respond better to N fertilization than the old genotypes, which is in agreement with the proposal of Gagliardi et al. [52] to limiting N inputs by adopting genotypes capable to optimize better the N fertilization.

The NM and NG were significantly related to weather conditions. They were higher in the year with higher rainfall (440.7 mm) than in the other two years (382.3 and 195.12 mm, respectively). These results were in agreement with those of [43], who reported that N concentration in the grain was affected by N fertilization but with a different trend as a function of weather conditions. This was also confirmed by the significant interaction between year and nitrogen. For the N effect, both NM and NG increased significantly with N increasing, confirmed also in semiarid environments by the results of many authors [24,53], who reported that increasing N fertilizer levels prompted increased N uptake by grain and by the whole plant at maturity. The NG over the whole study increased by an average value of 24.34% from N0 to N3. The mean grain N content was 54.54 kg N ha^{-1}, and it constituted 69.70% of total N uptake at maturity. These results also showed that the quantities of N uptake by the whole plant at maturity (NM) were greater than the quantities of N supply, whatever the initial richness of the soil in this element, except at the last N level, N3, where the N uptakes calculated by the N content were lower than the quantities of N supply. Therefore, under high fertilizer supply (N3) conditions, the quantities supplied by the soil were practically null, and we can hypothesize a significant loss of the unused N through the soil. In the present study, the studied genotypes showed different capacities to uptake and remobilize N. The more modern genotypes (Megress and GTAdur) expressed the best capacities with an average of 85.35 and 75.44 kg N ha^{-1} for NM and 61.78 and 54.32 kg N ha^{-1} for NG, respectively. Moreover, the two genotypes showed a higher ability in partitioning the total N uptake between different plant organs (NHI) in the studied environment, with an average value of 0.73 recorded by Megress and 0.72 by GTAdur. As expected, the modern genotypes were more efficient than the old genotypes for many traits.

NHI was significantly affected by year; the highest values were recorded in 2017, the dry year, with the lowest biomass (straw and grain); in contrast, NHI decreased along with the increasing N level, which is in agreement with the results of [43].

As a result, under semiarid conditions in Algeria, the N uptakes by the grain and by the whole plant are improved by the N supply with a different trend as a function of weather conditions.

4.2. Nitrogen Use Efficiency (NUE) and Its Components

For NUE, in general, our results indicated that NUE and its components (NupE and NUtE) were strongly affected by the climatic conditions each year and also by N increasing levels and genotypes. The response of NUE was dependent on the yearly climate, especially the rain distribution and amount during the vegetative phase of the growing cycle. In the present study, the mean of NUE averaged through the three N levels was only 50% of the world average, about 14.77 kg kg^{-1}. The lowest values of nUE and NUpE were recorded in the driest year 2016/17 (7.95 and 0.29 kg kg^{-1}, respectively). On the other hand, the highest values (19.87 and 0.74 kg kg^{-1}, respectively) were obtained in the first year (2015/16), which was characterized by more precipitation during the vegetative phase (Jan–Feb). In fact, there was a more favorable rain distribution throughout the cycle that allowed a higher accumulation of the total dry matter at maturity (DMM) vs. the other two years, and this assured high values of NUE. These results were confirmed by the high correlation between NUE and DMM (0.71 ***), which is in agreement with the results reported by [54]. The highest value of NUtE was obtained in the driest year with 27.34 kg kg^{-1}, which could be explained by the fact that the number of spikes m^{-2} and the total dry matter of straw at maturity were lower in that year, thus, increasing the ability of the plant to translate the N uptake to economic yield in the lower number of grains per unit area. As for the N effect on the efficiency parameters, the results showed that the NUE and its components NUpE and NUtE were negatively affected by the N increase. This can be expected with the increase in N availability, as similar results have been reported by many authors in different climates: temperate climate conditions [26,55], Mediterranean climate conditions [24,25,39,43,53], and semiarid conditions as well [22,56]. In López-Bellido et al. [24], they reported that NUE values in bread wheat at a maximum N fertilizer level of 150 kg N ha^{-1} were 49% lower than those obtained at 0 kg N ha^{-1}. In addition, Souissi et al. [46], reported that durum wheat grown under rainfed semiarid conditions was more efficient in water use and less efficient in N use.

In the present study, NUE values at maximum N fertilization (N3) of 120 kg N ha^{-1} were 43% lower than those obtained at N1 of 40 kg N ha^{-1}. However, in Ierna et al. [56], under rainfed semiarid conditions, the reduction was around 61%. This trend was explained by the negative relationship between N fertilization rates and NUE was ascribed by the non-linear pattern of yield response to N. In addition, López-Bellido et al. [24], explained this negative relationship by the fact that the grain yield rises less than the N supply in soil and fertilizer. In Delogu et al. [23], they explained the decrease in NUtE by the fact that the increase in crop N uptake with rising fertilizer levels is greater than the increase in grain yield. As for the genotype behavior, MBB and GTAdur had the highest values of NUE and NUtE, while Megress and GTAdur had higher values of NUpE.

The relative contribution of both components NUpE and NUtE to the variation of NUE was confirmed by the correlation results, where it was shown that the gain in NUE was more strongly associated with NUpE (0.90) than with NUtE (0.35), which is in agreement with the results obtained by [26]. Moreover, the present study showed that GY was dependent on NUpE (0.84 ***) and NUE (0.79 ***), which is in agreement with the results obtained by [24,33].

As a result, under semiarid conditions in Algeria, the NUE was more affected by the climatic conditions of the year, especially the rainfall during the vegetative phase of the growing cycle. Moreover, NUE and its components NUpE and NUtE were negatively affected by an N increase. The modern genotypes were more efficient than the old ones. These results are in accordance with the ones previously reported in the literature carried out in other environments. In fact, in rainfed conditions, Giuliani et al. [37] also showed that Ofanto and Simeto compared to the older cultivars Appio and Creso, highlighted a better adaptability to dry southern Italy environment. Our results fill the knowledge gap on NUE in durum wheat under semiarid conditions. However, looking ahead, it would be important to continue long-term experimentation with different sites and genotypes to make further innovations and improve N fertilization practices.

5. Conclusions

It was shown by the present study how the level of N fertilization improved the N uptake at maturity by the whole plant (NM) and by the grain (NG); however, no positive effects on either grain yield or marginal net return (MNR) were observed in the investigated area. Moreover, increasing the N application from 0 to 120 kg N ha^{-1} led to an economic loss of 13%. In other words, in the semiarid Algerian environment, the response to N is more elucidated in quality than in yield, and it is more dependent on the weather conditions of each year and on the cultivated genotypes. On the other hand, our results are in accordance with the previous studies, which confirm that the N supply negatively affected NUE and its components (NUpE, NUtE).

The constant higher performance for the yield and N-related traits of the more modern genotypes (tall and short: Megress and GTAdur, respectively) makes them more adapted to tolerate the climatic constraints during the flowering and grain filling but also to utilize N more efficiently in drought conditions.

The two modern genotypes, Megress and GTAdur, not only have the characteristics of being more productive but are also able to take up and remobilize the N in their total aerial part, as well as in their grains, more than the other investigated genotypes. This study targeted a small panel of common genotypes in Algeria. However, notwithstanding the small sample, the results presented are a clear indication of how a constant and faster genetic improvement would be necessary for the genotypes of wheat sown in the North African belt to cope with drier years and, at the same time, to better exploit the N inputs.

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