agronomy

MDPI

Article

Effects of Film-Bottomed Treatment on Absorbability and Translocation of Nitrogen in Spring Wheat in Arid Area

Zizhen Li [1], Xiaolei Zhou [1,*], Qing Tian [2,*], Low Pak Sum [3], Yuee Yan [4] and Xujiao Zhou [2]

[1] College of Forestry, Gansu Agricultural University, Lanzhou 730070, China; lizizhen1206@163.com
[2] Gansu Academy of Agricultural Sciences, Lanzhou 730070, China; 15117290190@163.com
[3] Academy of Sciences Malaysia, Kuala Lumpur 50480, Malaysia; lzz19921206@163.com
[4] Forest Inventory and Planning Institute of Gansu Province, Lanzhou 730020, China; 18894312970@163.com
* Correspondence: zhouxl@gsau.edu.cn (X.Z.); tqing@gsau.edu.cn (Q.T.)

Abstract: Plastic film-bottomed treatment (FBT) is a critical agricultural practice in arid regions, aimed at enhancing crop productivity by improving soil moisture retention and nutrient availability. However, the effects of different depths of film-bottomed treatment (DFBT) on nitrogen (N) absorption and translocation in spring wheat remain inadequately understood. We conducted a field experiment on sandy soil to investigate the effects of different DFBT depths (60, 70, 80, 90, and 100 cm) and on total N absorption amount (TNAA), total N translocation amount (TNTA) in all nutritive organs, grain nitrogen content (GN), and grain yield (GY). Morphological measurements included GY, GN, TNAA, and TNTA in the stem, sheath, leaf, spike axis, kernel husk (SAKH), and culm. The results showed that FBT significantly reduced soil moisture loss, with the 100 cm depth reducing soil leakage by 59.6% ($p < 0.001$). At the flowering stage, nitrogen derived from fertilizer (NDF) and soil nitrogen (NDS) were significantly higher at the 80 cm depth ($p < 0.001$). At maturity, the total nitrogen absorption amount (TNAA) and translocation amount (TNTA) in the main stem and across nutrient organs were significantly higher under the 80 cm DFBT ($p < 0.001$), leading to improved nitrogen use efficiency. The correlation between TNTA and GN was strongest at 80 cm ($p < 0.001$). Grain yield (GY) and GN were optimized at intermediate depths, particularly at 80 cm, suggesting this depth provides an optimal balance between water retention and drainage efficiency. These findings underscore the importance of optimizing DFBT depth, particularly at 80 cm, to achieve enhanced water retention, efficient nitrogen utilization, and improved crop productivity in arid agricultural systems. This research provides critical insights into sustainable agricultural practices under water-limited conditions, offering practical guidance for improving food security in arid regions.

Keywords: optimal film-bottomed depth (FBT); nitrogen uptake efficiency; nitrogen translocation pathways; spring wheat productivity; arid region soil management

check for updates

Academic Editor: Koffi Djaman

Received: 31 December 2024
Revised: 14 January 2025
Accepted: 17 January 2025
Published: 19 January 2025

Citation: Li, Z.; Zhou, X.; Tian, Q.; Sum, L.P.; Yan, Y.; Zhou, X. Effects of Film-Bottomed Treatment on Absorbability and Translocation of Nitrogen in Spring Wheat in Arid Area. *Agronomy* **2025**, *15*, 240. https://doi.org/10.3390/agronomy15010240

1. Introduction

Spring wheat (*Triticum aestivum* L.) is a crucial cash crop in the arid northwestern regions of China, where agricultural production is significantly limited by water scarcity and nitrogen (N) deficiency. The coarse-textured sandy soils common in these areas have poor water and nutrient retention capacities, which further exacerbate the challenges faced by local farmers [1,2]. Therefore, improving soil fertility and water use efficiency is essential for increasing crop yields and ensuring food security in these areas [3]. Recent advancements in soil management strategies, such as the development of superabsorbent polymers and soil conditioners, have shown promise in enhancing soil water retention and nutrient availability in arid environments [4,5].

Nitrogen is a key nutrient for plant growth and directly impacts wheat yield and quality. It promotes leaf area expansion, increases photosynthetic rates, and extends the functional period of leaves, enhancing the accumulation of photosynthetic products [6]. Efficient N uptake and remobilization during critical growth stages, such as post-anthesis, are essential for improving grain protein content and overall yield [7,8]. Recent research has emphasized the role of nitrogen remobilization and advanced techniques, such as stable isotope labeling and high-throughput phenotyping, in improving nitrogen use efficiency (NUE) [9,10]. These approaches highlight the importance of enhancing N uptake during later growth stages to optimize grain quality [11].

Drought is a primary constraint on wheat production in arid and semi-arid regions. Soil moisture deficits reduce dry matter accumulation and disrupt nutrient redistribution within the plant, negatively impacting plant health and yield [12]. In response to the challenges faced by agriculture in arid regions, extensive research efforts have been directed toward breeding techniques and cultivation practices to optimize water utilization efficiency, such as dryland farming and nutrient management [13]. Film-Bottomed Treatment (FBT) has shown promise in mitigating soil drought by reducing soil compaction and preventing water loss through surface evaporation, thus enhancing crop growth conditions [2,14]. Advanced simulations using soil-water-crop models have also demonstrated the potential of FBT in maintaining higher soil moisture levels under water-limited conditions [15].

Since 2016, FBT has been applied to approximately 6000 hectares in the Hexi Corridor. This has significantly improved wheat plant height, leaf area index, and dry weight [16,17]. While many studies have explored the effects of factors such as film-bottomed depth, nitrogen application, and irrigation on spring wheat growth and yield [2,18,19], research specifically focusing on their impacts on total nitrogen absorbability amount (TNAA) and total nitrogen translocation amount (TNTA) remains limited. Addressing this research gap is crucial for optimizing nitrogen management and increasing wheat productivity in drought-prone areas. Existing studies have assessed how FBT affects water retention and soil nutrient dynamics [20]. However, its role in nitrogen translocation mechanisms has not been fully explored.

Research on the depth of film-bottomed treatment (DFBT) and its effects on TNAA and TNTA in spring wheat is critical for improving nitrogen management in arid regions [21,22]. DFBT helps retain soil moisture and influences root distribution, both of which are important for nitrogen uptake and translocation [23]. By creating a favorable microenvironment, DFBT enhances root access to nitrogen reserves, especially under fluctuating water conditions. This reduces the negative effects of water stress on nitrogen uptake and efficiency. Advanced root imaging techniques show that DFBT improves root morphology and root-soil interactions, leading to better nutrient absorption in arid environments [24]. Understanding how DFBT affects TNAA and TNTA provides valuable insights into nitrogen metabolism in wheat. This knowledge can support breeding programs to develop wheat varieties with improved nitrogen use efficiency (NUE), a critical trait for sustainable and productive agricultural systems [25].

This study evaluates the effects of different DFBT (60, 70, 80, 90, and 100 cm) on TNAA and TNTA in spring wheat. We analyzed nitrogen dynamics in nutrient organs such as stems, sheaths, leaves, spike axes, kernel husks (SAKH), and main culms. Additionally, we examined the relationship between grain nitrogen (GN), grain yield (GY), and the nutritional status of these organs under varying DFBT. We hypothesize that an intermediate DFBT depth (approximately 80 cm) will optimize nitrogen uptake and translocation efficiency by improving soil moisture retention and creating a favorable root environment.

This is expected to enhance nitrogen use efficiency, grain yield, and grain quality, offering a sustainable solution for nitrogen and water management in arid agricultural systems. This research aims to fill a critical gap in understanding how DFBT affects nitrogen dynamics in spring wheat, contributing to the development of optimal nitrogen and water management strategies to improve productivity and sustainability in arid environments.

2. Materials and Methods

2.1. Experimental Site

The study was carried out in a field of the Provincial Laboratory of Arid Agroforestry, Gansu Agricultural University (37°26′ N, 103°45′ E, 1665 m height above sea level), located on the southern margin of the Tengger desert, a transitional zone between desert and oasis. The physicochemical properties of the soil at the test site were analyzed using standardized methods. Soil pH was measured in a 1:2.5 soil-to-water suspension with a pH meter (Orion 710A, Thermo Fisher Scientific, Waltham, MA, USA). Organic matter content was determined via the Walkley–Black method (Merck KGaA, Darmstadt, Germany). Total nitrogen and total phosphorus were quantified using the Kjeldahl digestion (FOSS Kjeltec 8400, FOSS, Hilleroed, Denmark) and perchloric acid digestion methods, respectively (Sigma-Aldrich, St. Louis, MO, USA). Available phosphorus was measured using the Olsen method (Sigma-Aldrich, St. Louis, MO, USA), and available potassium was assessed via flame photometry after ammonium acetate extraction (FP-640, Horiba Scientific, Kyoto, Japan). Water-soluble chloride was determined through silver nitrate titration following water extraction (reagents from Sinopharm Chemical Reagent Co., Ltd., Shanghai, China). The physicochemical properties of the soil at the test site were gray desert soil with pH 7.8, organic matter content of 2.6 g kg^{-1}, total nitrogen content of 0.27 g kg^{-1}, total phosphorus content of 0.62 g kg^{-1}, available phosphorus content of 3.08 mg kg^{-1}, available potassium content of 4.62 mg kg^{-1}, and water-soluble Cl 0.21%, with low levels of organic matter, total N and phosphorus (P), available P and K (Tables S1 and S2). The meteorological data from the TPDC (https://data.tpdc.ac.cn, accessed on 14 August 2024) showed that the average temperatures during the growing period of spring wheat in 2014–2016 were 18.6, 19.2, and 20.7 °C, and the annual rainfall was 209.2, 194.5, and 217.2 mm, respectively. There is little variability compared to the 2000–2016 long-term average temperature (18.9 °C) and average rainfall (202.9 mm) (Figure S1). The climate is arid, with an average daily evaporation during this time of 3038.5 mm, mean annual temperature of 8.2 °C, ≥10 °C active accumulated temperature of 2988.7 °C, and mean annual wind velocity of 3.5 m s^{-1} [24].

2.2. Field Layout and Experimental Details

A field experiment was conducted during the 2014, 2015, and 2016 growing seasons using spring wheat cultivar 'Yongliang-2', selected for its high disease resistance and superior yield performance in the region [26]. Sowing was carried out annually on March 17th at a sowing rate of 144 kg ha^{-1}. The experiment was conducted in irrigated farmland, with treatment plots centrally located to ensure uniform conditions. Each treatment plot was 20 m × 20 m, which was established by digging a 20 m × 20 m pit. All residual plant roots were removed, and the bottom and sidewalls were lined with 0.05 mm thick plastic film before backfilling with the original sandy soil [24,26]. The experimental design included six treatments: five DFBTs with buried depth levels of 60, 70, 80, 90, and 100 cm, and a control treatment (no DFBT). Each treatment served as a main plot and was replicated four times. The treatment plots were randomly distributed within the study area to minimize spatial variability and ensure unbiased results. A total of 24 treatment plots were established, with a combined experimental area of 0.96 ha. To further enhance the design, a buffer zone of 5 m was maintained between adjacent plots to prevent treatment interactions.

Before sowing, the field was plowed with a tooth harrow, and 10 kg P ha^{-1} (Sierte Fertlizer Industry Co., Ltd., Ningguo, China), 25 kg K ha^{-1} (Asia-Potash International Investment Co., Ltd., Guangzhou, China), and 160 kg N ha^{-1} were applied manually in all plots. The nitrogen source was ^{15}N-labeled urea (10% enrichment and 46% nitrogen content) (Guangzheng Chemical Co., Ltd., Dongying, China), broadcast manually and incorporated into the soil through plowing to ensure uniform distribution and minimize volatilization. Fungicides (Propiconazole, Sinochem International, Beijing, China) and insecticides (Imidacloprid, China National Chemical Co., Beijing, China) were applied for disease and insect control, and weeds were manually removed throughout the growing season. The irrigation method used in this study was flood irrigation, a common practice in the Hexi Corridor region of China. The irrigation water was sourced from a local canal network fed by melted snow and rainfall, typical of arid regions near the Tengger desert. Water quality was monitored, with salinity levels below 0.4 dS m^{-1}, meeting the standard for agricultural irrigation, and nitrogen concentrations were negligible (<0.2 mg L^{-1}), ensuring minimal contribution to plant nitrogen uptake. In this study, irrigation water was uniformly applied across the treatment plots using channels designed to direct water flow evenly. Irrigation was carried out at critical growth stages of spring wheat—emergence, tillering, stem elongation, and milking. A total irrigation volume of 300 mm was applied over the growing season, aligning with the average evapotranspiration for spring wheat in the region, which is approximately 220.3 mm [27,28]. The yield of crops is closely related to the sensitivity of plants to water stress at different growth stages (Figure 1) [24,29,30]. High soil available water typically promotes tillering in spring wheat, which is particularly sensitive from tillering to the milking and maturity stages [31]. The total cost of plastic mulch placement varied according to the depth of burial (DFBT). Information on the cost of installing the film, the effect of depth on the cost, and detailed information on the increased production required to balance these costs is in Supplementary Materials Table S4.

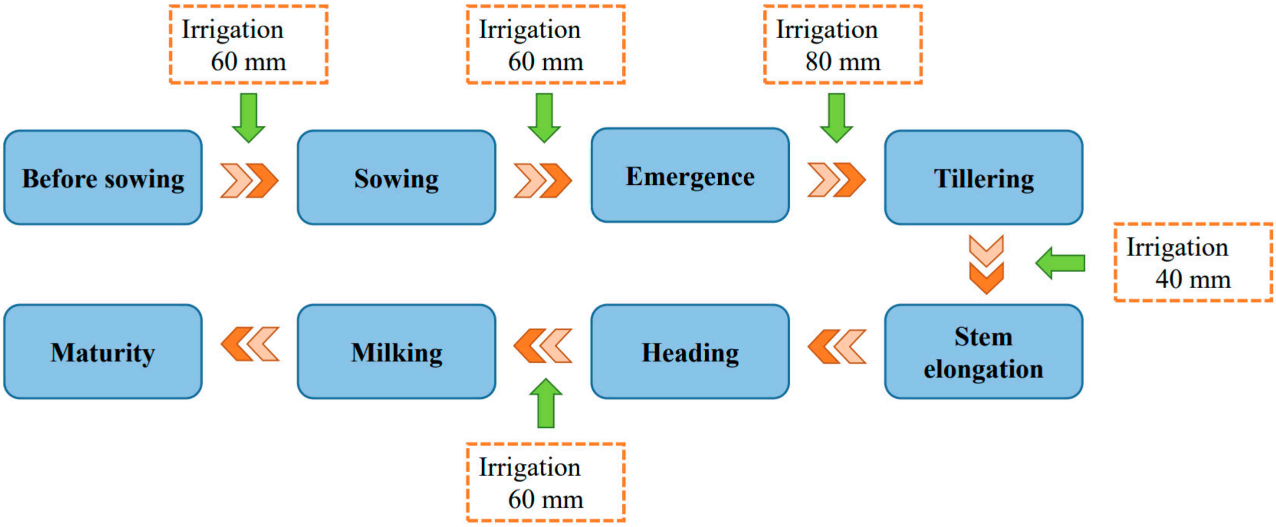

Figure 1. Crop water irrigation at given growth stages for spring wheat.

2.3. Assay Item and Methods

Spring wheat at anthesis and maturity were harvested by hand from the entire above-ground portion of the wheat plant in each sample plot each year. To ensure consistency, each plot was harvested on the same day. After harvesting, above-ground plants were divided into Stem, Sheath, Leaf, SAKH, Main culm, and Seed according to the different physiological stages, and then the collected samples were washed separately with distilled water to remove impurities and dried in an oven at 70 °C to a constant weight, and weighed to determine the dry matter mass of the individual samples. Next, all samples were ground into powder for further analysis.

Soil moisture was monitored on a weekly basis using the neutron probe access tubes (Frequency Domain Reflectometry (FDR) ATS1 PR1/4, Delta-T Devices Ltd., Hatfield, UK) with a diameter of 4 cm were installed in the center of each plot [32]. Neutron probe access tubes were located at the center of each of the different DFBT plots. The N content of various plant organ materials was determined using the micro-Kjeldahl method [33]. The method consisted of two main steps: acid digestion of plant material and the colorimetrical measurement of N as ammonia in the digested plant samples after converting it into indophenol dye [34].

The use of ^{15}N isotope labeling in plant nutrition research is pivotal for examining nitrogen sources, uptake, translocation, and utilization efficiency. By analyzing ^{15}N content in plants, researchers can distinguish between nitrogen absorbed from fertilizers and soil, facilitating the optimization of nitrogen fertilizer application [35,36]. This technique also allows for the assessment of nitrogen use efficiency (NUE), providing insights into the effectiveness of fertilization practices and reducing nitrogen losses [37].

The steps in the calculation are as follows:

Using ZHT-O_2, analyze ^{15}N abundance.

TNAA = dry weight of plant × N content of plant (%).

The rate of N derived from fertilizer (RNDF) (%) = ^{15}N per centum of plant sample under fertilizer (%)/^{15}N per centum of fertilizer (%) × 100.

Plant absorbed N derived from fertilizer (NDF) = amount of plant absorbed total N × RNDF (%).

Plant absorbed N derived from soil (NDS) = TNAA—plant absorbed N derived from fertilizer.

The rate of NDS = NDS/TNAA × 100 [38].

TNTA = TNAA at anthesis—TNAA at maturity.

2.4. Statistical Analyses

A two-way analysis of variance (ANOVA) was conducted to test whether the N absorbability and translocation in all nutritive organs, as well as GN and GY of spring wheat at the anthesis and maturity stages, differed between treatments across different years. If the ANOVA indicated significant differences, Tukey's multiple comparison test was used to determine pairwise differences between treatments. Linear regression analysis was performed to examine the relationship between GN, GY, and TNTA of all nutritive organs. Regression analysis was conducted across treatments at anthesis and maturity stages using plot values. Principal Component Analysis (PCA) was utilized to identify key factors driving the observed variations. All data transformations and analyses were carried out using SAS 9.4 [39] and Origin 2022 software.

3. Results

3.1. Soil Moisture as Affected by Different DFBT

Soil moisture declined during the spring wheat growing season across all treatments, including different DFBT depths and the control. However, the application of DFBT significantly reduced soil moisture loss through leakage compared to the control. Among the DFBTs, deeper burial depths (e.g., 90 cm and 100 cm) were particularly effective in conserving soil moisture, with reductions in leakage of up to 56.8% and 59.6%, respectively (Figure 2, Table S3). Statistical analyses confirmed significant differences in soil moisture content among all treatments at various growth stages, including before sowing, emergence, tillering, stem elongation, heading, milking, and maturity ($p < 0.001$ for all stages). There was a positive correlation between DFBT depth and soil moisture content under the same irrigation regime, indicating that deeper FBT installations consistently maintained higher soil moisture levels (Figure 2). In general, the order of soil moisture content (0–40 cm depth) of different treatments was 60 cm < 70 cm < 80 cm < 90 cm < 100 cm DFBT.

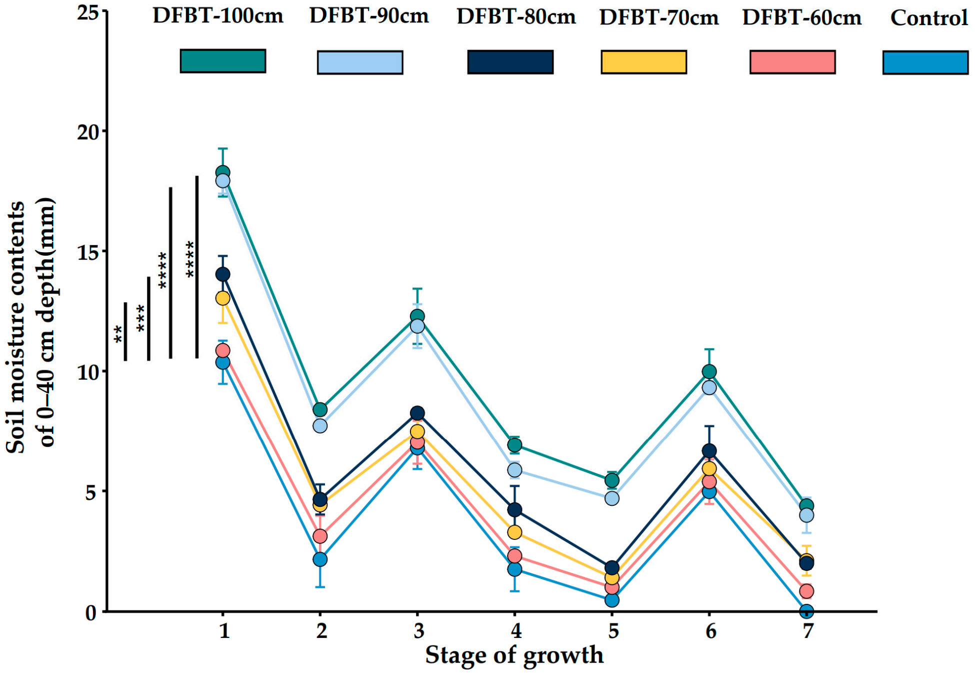

Figure 2. Soil moisture contents of 0–40 cm depth in different stages of spring wheat growth season. 1: From before sowing to sowing; 2: from sowing to emergence; 3: from emergence to tillering; 4: from tillering to stem elongation; 5: from stem elongation to heading; 6: from heading to milking; 7: from milking to maturity. The colors of different lines represent five DFBTs at different depths (60, 70, 80, 90, and 100 cm) and one control treatment (no DFBT). **, *** and **** represent $p < 0.01$, $p < 0.001$, and $p < 0.0001$, respectively.

3.2. Effect of DFBT on TNAA

Absorbed NDF in each spring wheat organ was significantly different among all treatments at anthesis ($p < 0.001$ for stem; $p < 0.001$ for sheath; $p < 0.001$ for leaf; $p < 0.001$ for SAKH; $p < 0.001$ for main culm). Compared to the control treatment, DFBT significantly increased the NDF, and the significantly largest NDF always occurred at 90 cm DFBT at anthesis stage (Table 1).

Table 1. Effects of different DFBT on NDF in all nutritive organs of spring wheat from N sources at anthesis.

Treatments	NDF/Depth (cm)										Control		F-Value
	60		70		80		90		100				
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Stem (mg g^{-1})	0.94 C	1.34	1.32 A	0.77	1.18 B	0.85	1.27 AB	0.47	1.32 A	0.03	0.97 C	1.03	63.84 ***
Sheath (mg g^{-1})	0.66 B	0.43	0.99 A	1.19	1.09 A	0.64	1.04 A	0.36	0.99 A	0.76	0.72 B	1.41	66.53 ***
Leaf (mg g^{-1})	1.26 D	0.13	1.05 F	0.41	2.22 C	0.04	2.49 B	1.13	2.83 A	0.82	1.76 E	1.34	706.90 ***
SAKH (mg g^{-1})	1.62 B	1.25	1.73 A	0.84	1.65 B	0.86	1.58 C	0.65	1.28 E	1.08	1.43 D	0.86	610.08 ***
Main culm (mg g^{-1})	4.98 C	0.95	6.23 B	0.17	6.45 B	1.26	6.73 A	0.94	4.24 D	0.95	4.80 C	0.52	586.34 ***

Capital letters indicate 0.01 extremely significant level. *** Significance at $p < 0.001$.

Absorbed NDS in each spring wheat organ was significantly different among all treatments at anthesis ($p < 0.001$ for stem; $p < 0.001$ for sheath; $p < 0.001$ for leaf; $p < 0.001$

for SAKH; $p < 0.001$ for main culm). Comparing the control treatment, DFBT significantly increased the NDS, and the significantly largest NDS always occurred at 80 cm DFBT at anthesis (Table 2).

Table 2. Effects of different DFBT on NDS in all nutritive organs of spring wheat from N sources at anthesis.

Treatments	NDS/Depth (cm)										Control		F-Value
	60		70		80		90		100				
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Stem (mg g^{-1})	5.13 B	0.54	4.93 C	0.20	5.62 A	1.43	5.20 B	0.24	3.91 E	0.29	4.05 D	1.41	2085.98 ***
Sheath (mg g^{-1})	3.99 C	0.50	4.45 A	0.71	4.19 B	1.08	4.16 B	0.85	2.82 D	1.26	2.80 D	0.21	1530.41 ***
Leaf (mg g^{-1})	4.01 F	1.09	7.97 B	0.51	8.94 A	1.12	7.71 C	0.84	6.49 D	0.83	6.05 E	1.19	5783.21 ***
SAKH (mg g^{-1})	6.53 C	1.12	6.85 B	0.13	7.21 A	0.64	6.63 C	0.33	5.26 E	1.40	5.40 D	1.09	2065.33 ***
Main culm (mg g^{-1})	19.67 D	1.32	24.19 B	0.59	25.96 A	0.54	23.70 C	0.85	18.48 E	0.77	18.29 E	0.59	6003.15 ***

Capital letters indicate 0.01 extremely significant level. *** Significance at $p < 0.001$.

TNAA in each spring wheat organ was significantly different among all treatments at anthesis ($p < 0.001$ for stem; $p < 0.001$ for sheath; $p < 0.001$ for leaf; $p < 0.001$ for SAKH; $p < 0.001$ for main culm). DFBT significantly increased the TNAA except for the control, and the significantly largest TNAA always occurred at 80 cm DFBT at anthesis (Table 3).

Table 3. Effects of different DFBT on TNAA in all nutritive organs of spring wheat from N sources at anthesis.

Treatments	TNAA/Depth (cm)												
	60		70		80		90		100		Control		F-Value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Stem (mg)	6.45 B	0.31	6.11 C	0.37	6.89 A	0.85	6.52 B	1.04	4.88 D	0.43	4.98 D	0.31	982.56 ***
Sheath (mg)	4.98 C	0.32	5.55 A	1.13	5.24 B	0.42	5.16 BC	1.1	3.54 D	0.49	3.46 D	1.11	827.04 ***
Leaf (mg)	5.06 E	0.34	10.19 C	0.94	11.42 A	0.62	10.55 B	0.44	7.75 D	0.27	7.81 D	0.44	4154.85 ***
SAKH (mg)	8.15 C	0.38	8.57 B	0.44	8.86 A	0.84	8.21 C	0.45	6.54 E	0.15	6.83 D	0.98	2681.57 ***
Main culm (mg)	24.65 C	0.48	30.42 B	0.80	32.41 A	0.43	30.43 B	0.34	22.71 D	0.04	23.08 D	0.45	4107.79 ***

Capital letters indicate 0.01 extremely significant level. *** Significance at $p < 0.001$.

The TNAA, NDF, and NDS in each spring wheat organ at maturity were similar with one at anthesis, and the significantly largest TNAA, NDF, and NDS always occurred at 80 cm DFBT.

3.3. Effect of DFBT on TNTA in Nutritive Organs

There were significant differences in TNTA of stem, sheath, leaf, and SAKH among the six treatments. The largest value of TNTA occurred in 80 cm DFBT, while the smallest value of TNTA in four nutritive organs was observed in the control (Table 4). Compared to the control, the effects of FBT on TNTA were significant, and TNTA in all nutritive organs exhibited positive responses to FBT (Table 4).

Table 4. Effects of different DFBT on TNTA in nutritive organs at maturity.

Treatments	60 cm		70 cm		80 cm		90 cm		100 cm		Control		F-Value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Stem (mg g^{-1})	4.89 A	0.73	3.78 B	0.96	3.72 B	0.45	3.55 C	1.15	1.88 D	0.88	3.59 C	1.01	904.21 ***
Sheath (mg g^{-1})	3.61 B	0.83	3.77 AB	0.51	3.95 A	0.98	2.49 C	0.15	1.04 E	1.02	2.20 D	0.72	542.09 ***
Leaf (mg g^{-1})	1.87 F	1.06	7.52 B	0.65	8.14 A	1.06	5.47 C	0.31	2.88 E	0.59	4.80 D	0.43	3103.33 ***
SAKH (mg g^{-1})	3.88 C	1.16	6.67 A	1.11	6.61 A	0.57	6.07 B	0.83	3.65 D	0.58	3.86 C	0.67	2465.84 ***
Total (mg g^{-1})	14.25 D	0.26	21.74 B	0.72	22.43 A	0.93	17.58 C	1.04	9.44 E	0.13	14.45 D	0.59	3434.29 ***

For each component, the mean values with the same letters among organs are not significantly different at 0.0001 level of probability. *** Significance at $p < 0.001$.

3.4. Relationships Between TNTA in All Nutritive Organs, and GN and GY

The data analysis revealed that the patterns of trait association between GN and TNTA across all nutritive organs were consistent under different treatments. Consequently, the Pearson correlation coefficients between TNTA of all nutritive organs and GN were calculated for the data set during the maturity stage (Table 4).

GN was positively correlated with leaf TNTA across all plant organs, with the strongest correlation observed under the 80 cm DFBT ($p < 0.001$). Significant positive correlations were also found for the 70 cm ($p < 0.01$), 60 cm ($p < 0.05$), and 90 cm ($p < 0.05$) treatments. The weakest positive correlation was observed under the control ($p < 0.05$).

The strongest correlation between GN and sheath TNTA occurred under the 80 cm DFBT ($p < 0.001$). Significant correlations were also observed under the 70 cm ($p < 0.05$), 90 cm ($p < 0.05$), and 100 cm ($p < 0.05$) treatments. Additionally, GN showed positive correlations with stem TNTA under the 70 cm ($p < 0.05$) and 90 cm ($p < 0.05$) treatments, as well as with SAKH TNTA under the 70 cm DFBT ($p < 0.05$).

For the 60 cm treatment, significant correlations were observed between the sheath and leaf ($p < 0.05$) and between the stem and SAKH ($p < 0.01$). In the 70 cm depth treatment, the stem was positively correlated with the leaf ($p < 0.05$). Under the 80 cm depth treatment, the leaf was positively correlated with the sheath ($p < 0.01$) but negatively correlated with SAKH ($p < 0.05$). There was a significant negative correlation between the sheath and SAKH ($p < 0.05$).

For the 90 cm depth treatment, the stem was positively correlated with the sheath ($p < 0.05$) but negatively correlated with the leaf ($p < 0.05$). There was a significant positive correlation between the sheath and the leaf ($p < 0.05$) and a significant negative correlation between the sheath and SAKH ($p < 0.01$).

In the 100 cm depth treatment, SAKH was negatively correlated with the sheath ($p < 0.05$) and the leaf ($p < 0.05$). The sheath was negatively correlated with the stem ($p < 0.05$) but positively correlated with the leaf ($p < 0.05$). Under the control condition, the stem was negatively correlated with the sheath ($p < 0.05$) but positively correlated with SAKH ($p < 0.05$).

The relationships among all nutritive organs and GY showed a similar pattern.

3.5. Relationship of Different DFBT with NDF, NDS, TNAA and TNTA

The PCA results (Figure 3) show that PC1 and PC2 account for 98.8% and 0.9% of the variance in the data, respectively, with a cumulative contribution rate of 99.6%. This indicates that these two principal components are the main factors influencing the nitrogen content in different forms. The distribution of groups along the PC1 and PC2 axes exhibits clear differentiation, particularly for TNTA, which is significantly separated from NDF, NDS, and TNAA in the principal component space. This separation is attributed to TNTA representing the total nitrogen translocation amount in the nutritional organs of spring wheat at maturity, demonstrating distinct characteristics compared to NDF, NDS, and TNAA, which represent the nutrient organs at anthesis. Furthermore, the concentrated data distribution of NDF reflects its low internal variability. The overlap of NDF and NDS with TNAA in the principal component space suggests similarities or overlapping data characteristics among these variables. In contrast, the relatively large confidence ellipse of TNAA indicates higher internal variability within this group. An analysis of the principal component loadings reveals that the high variance explained by PC1 underscores its significant role in capturing the overall variability in the data. Specifically, the absolute value of the loading vector for the 80 cm DFBT depth in PC1 is the largest, exceeding 0.5. This further highlights that the 80 cm DFBT depth achieves an optimal balance in nitrogen management, thereby significantly enhancing both the productivity and nutrient use efficiency of spring wheat.

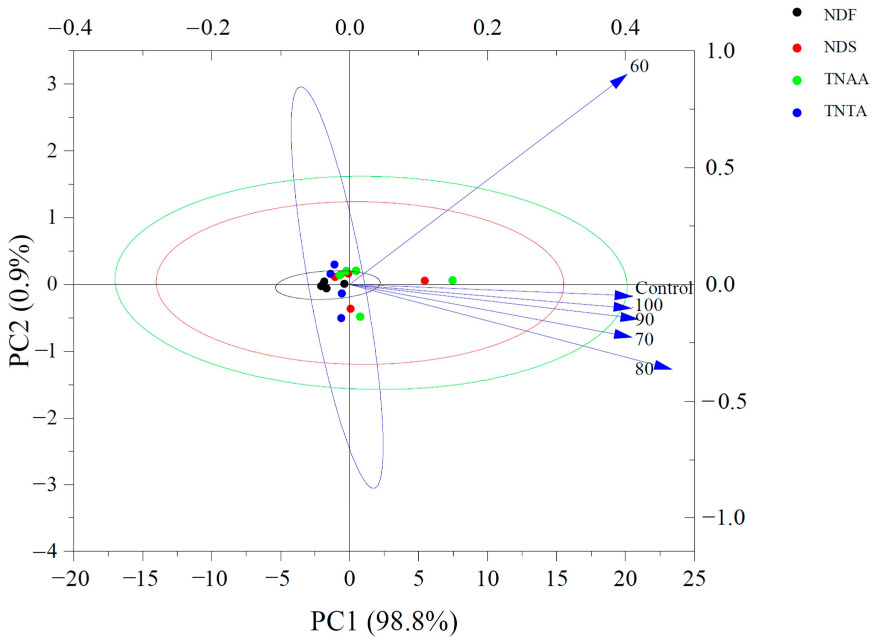

Figure 3. PCA of different DFBTs with NDF, NDS, TNAA, and TNTA. NDF, NDS, TNAA, and TNTA represent fertilizer nitrogen, soil nitrogen, total nitrogen absorption amount, and total nitrogen translocation amount, respectively. 60, 70, 80, 90, 100, and control represent five DFBTs at different depths (60, 70, 80, 90, and 100 cm) and a control treatment (no DFBT), respectively.

3.6. Absolute GY—GN Relationships

Absolute GY and GN were illustrated in Figures 3 and 4. The mean value ranged from 1863 ± 64.47 to 5701.55 ± 115.85 kg ha^{-1} ($p < 0.001$) and 17.97 ± 0.64 to 31.23 ± 0.28 mg kg^{-1} ($p < 0.001$) for GY and GN, respectively. The differences in GN and GY under the same DFBT across different years were not statistically significant ($p > 0.05$). It was obvious that poor grain yield responses to DFBT were observed in control and 60 cm and, 100 cm DFBT due to soil moisture stress in the former and waterlogged conditions in the latter (Figures 4 and 5).

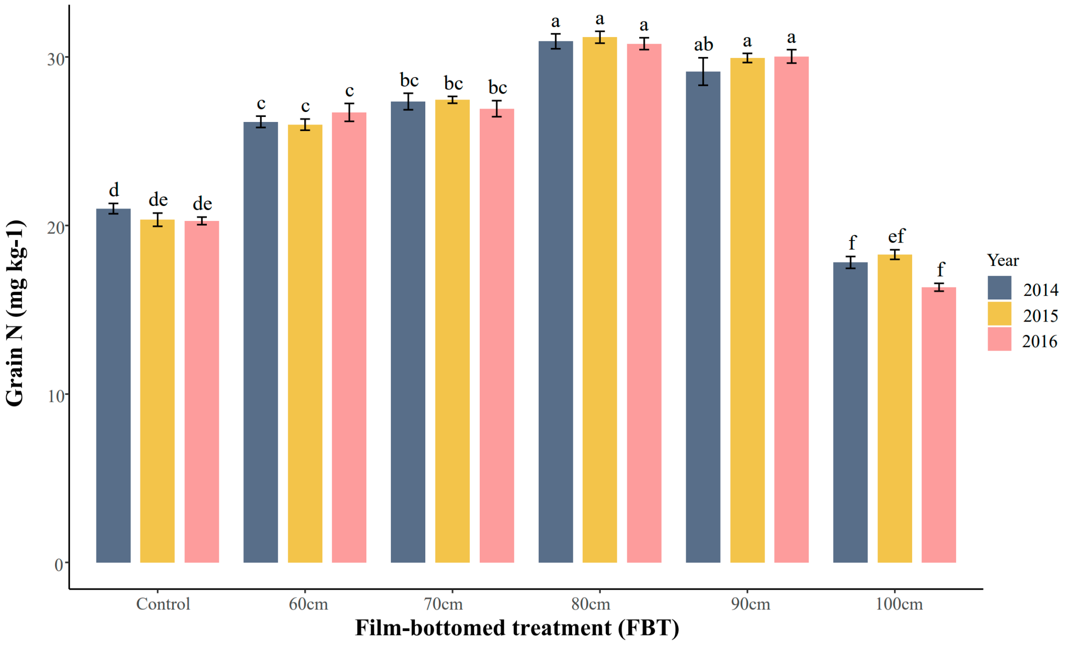

Figure 4. Effects of different FBT treatments on GN of spring wheat at the maturity stage across different years. Lowercase letters on the bars indicate comparative results at a significant level of 0.01 under different DFBTs (Tukey’s multiple comparisons test).

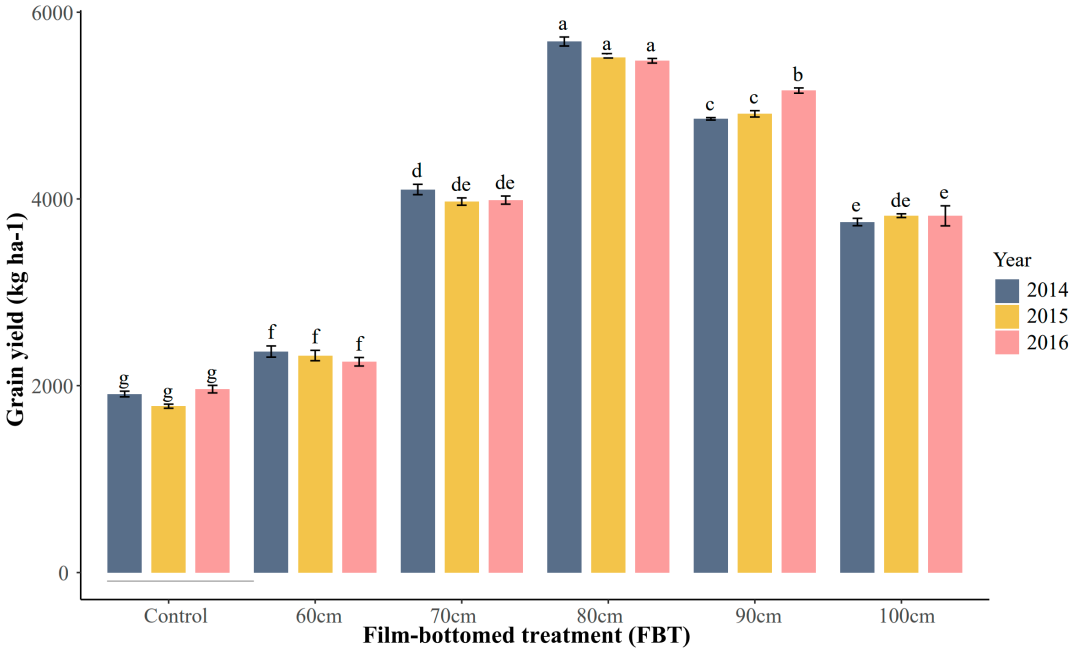

Figure 5. Effects of different FBT treatments on GY of spring wheat at the maturity stage across different years. Lowercase letters on the bars indicate comparative results at a significant level of 0.01 under different DFBTs (Tukey's multiple comparisons test).

4. Discussion

4.1. Effectiveness of Film-Bottomed Treatment (FBT) in Soil Moisture Conservation

The application of different DFBTs demonstrated significant impacts on soil moisture retention during the growth of spring wheat. The findings indicate a notable reduction in soil moisture loss due to leakage, particularly when DFBT was implemented compared to the control. This suggests that the use of FBT is an effective strategy to conserve soil moisture, which is crucial for optimizing water use efficiency in agricultural practices.

The data showed that soil moisture content increased with the depth of the FBT, reaching its highest under the 100 cm DFBT. This trend can be attributed to the greater barrier effect provided by deeper treatments, which likely minimizes water percolation losses and maintains higher soil moisture levels. The significant positive correlation between DFBT depth and soil moisture content under the same irrigation regime further supports the effectiveness of deeper FBT in conserving water. These results are consistent with previous studies that have highlighted the benefits of soil moisture conservation through various mulching and barrier techniques [40,41].

The two-way ANOVA results indicated significant differences in soil moisture content among the treatments across all seven observation periods. Notably, during critical growth stages, such as stem elongation and heading, the soil moisture content in the control plots was close to or below the wilting point for spring wheat. This moisture deficit likely contributed to suboptimal plant growth and yield, underscoring the importance of effective soil moisture management [42]. In contrast, the higher soil moisture levels maintained under FBT treatments suggest that these methods could mitigate drought stress, particularly during sensitive developmental stages.

The findings also highlight the potential limitations of the control treatment, where soil moisture levels were significantly lower, often dropping below critical thresholds for plant survival and productivity. The consistent order of soil moisture content (60 cm < 70 cm < 80 cm < 90 cm < 100 cm DFBT) observed in this study reinforces the necessity of considering appropriate DFBT depths to optimize water retention and enhance crop performance [43].

Similar studies also support these findings. Sağlam et al. (2015) [44] investigated the effects of different tillage depths on soil moisture and crop yield, revealing that deep tillage significantly improved soil moisture content and crop productivity. Additionally, Lu et al. (2020) [45] highlighted that increasing soil covering thickness could enhance soil temperature and moisture conditions, thereby promoting root development and nutrient uptake. However, it is worth noting that excessively deep DFBT may raise agronomic management costs and labor intensity and could even negatively impact soil structure. Therefore, identifying an optimal DFBT depth to balance water retention and resource inputs remains a critical direction for future research [11]. Future research should focus on optimizing DFBT depths for different crops and soil types, integrating water and nutrient management to improve efficiency, leveraging technological innovations for precision agriculture, and assessing long-term ecological impacts to ensure sustainable agricultural production.

4.2. Enhanced Nitrogen Uptake and Utilization Through DFBT

The impact of different DFBT on nitrogen absorption in spring wheat organs at anthesis and maturity stages reveals significant trends that underscore the importance of optimizing DFBT depths for nutrient management. The findings indicate that DFBT significantly enhances nitrogen absorption, NDF and NDS, across various wheat organs compared to the control. Notably, the optimal depth for maximizing TNAA appears to be at the 80 cm and 90 cm DFBTs, depending on the nitrogen source.

The two-way ANOVA results indicate substantial differences in NDF among all treatments, with the highest values consistently observed at the 90 cm DFBT depth at the anthesis stage. This suggests that deeper DFBTs may create favorable conditions for nitrogen uptake from fertilizer, possibly due to improved soil moisture retention and reduced nitrogen leaching [46]. The increased NDF could also be attributed to enhanced root growth and activity in deeper soil layers, allowing more effective utilization of applied nitrogen [47].

Similarly, the significantly higher NDS observed at the 80 cm DFBT indicates that this depth is particularly effective in facilitating nitrogen uptake from soil. The consistent pattern of increased NDS with deeper DFBTs suggests that these methods not only enhance soil moisture retention but also improve nitrogen mineralization and availability in the soil profile [43]. This enhancement in nitrogen availability could be due to the reduced soil temperature fluctuations and improved microbial activity associated with greater soil moisture content under deeper DFBT [48].

The observed trends in TNAA at both anthesis and maturity stages further emphasize the benefits of optimal DFBT depths. The significantly largest TNAA at the 80 cm DFBT highlights its effectiveness in maximizing nitrogen assimilation and accumulation in wheat organs. This is consistent with the patterns seen for both NDF and NDS, suggesting that the 80 cm DFBT provides a balanced environment that optimizes both nitrogen sources [49]. The fact that TNAA, NDF, and NDS patterns are similar at both anthesis and maturity stages indicates that these benefits are sustained throughout the crop growth cycle, potentially leading to improved grain yield and quality.

These findings have practical implications for agricultural management, particularly in regions where nitrogen use efficiency and soil moisture conservation are critical concerns. The application of DFBT at optimal depths can significantly enhance nitrogen uptake and utilization, thereby reducing the need for excessive fertilizer application and minimizing environmental impacts.

4.3. Optimized Nitrogen Translocation and Utilization in Wheat Organs

The application of different DFBTs has demonstrated significant effects on the TNTA in the nutritive organs of spring wheat, specifically the stem, sheath, leaf, and SAKH. The observed differences in TNTA across the six treatments underscore the importance of DFBT in enhancing nutrient translocation within the plant, a crucial factor for optimal growth and yield. The results show that the 80 cm DFBT consistently resulted in the highest TNTA values across all nutritive organs, while the control treatment exhibited the lowest TNTA. This suggests that the application of DFBT at 80 cm depth creates a more favorable microenvironment for nitrogen uptake and translocation. The significant increase in TNTA under DFBTs compared to the control indicates that DFBT not only enhances nitrogen absorption but also improves the efficiency of nitrogen utilization within the plant. This can be attributed to several factors, including improved soil moisture retention, reduced soil temperature fluctuations, and enhanced root growth [50].

The positive response of TNTA to DFBT across all nutritive organs highlights the role of optimized soil moisture and temperature conditions in promoting the efficient translocation of nitrogen from vegetative tissues to reproductive organs. This is particularly critical during the grain-filling period, where efficient nutrient translocation can significantly impact final grain yield and quality [42]. The enhanced TNTA under DFBTs may also be associated with better plant physiological conditions, such as increased leaf area index and photosynthetic efficiency, which contribute to greater biomass production and nutrient accumulation [15]. The differential response of TNTA among the various organs also indicates that nitrogen partitioning within the plant can be influenced by the depth of DFBT. For instance, the significant increase in TNTA in the stem and sheath under deeper DFBTs suggests that these organs play a crucial role in nitrogen storage and translocation, potentially serving as temporary sinks for nitrogen before it is remobilized to the grains [51]. This efficient internal nitrogen cycling within the plant may help to sustain growth and development under varying environmental conditions.

Overall, the findings underscore the importance of optimizing DFBT depths for maximizing nitrogen use efficiency and improving crop performance. The consistent enhancement of TNTA across different nutritive organs at the 80 cm DFBT indicates that this depth provides an optimal balance of soil moisture and temperature conditions, leading to improved nitrogen translocation.

4.4. Correlation Between Nitrogen Dynamics and Grain Production

The data analysis reveals distinct patterns in the relationships between TNTA in different nutritive organs and GN, as well as GY, under various DFBTs. The consistent positive correlation between TNTA and GN across different organs and treatments indicates that enhanced nitrogen translocation correlates strongly with increased reproductive success, highlighting the critical role of nitrogen management in optimizing crop yield potential.

The strongest correlation was observed between the sheath of TNTA and GN, particularly under the 80 cm DFBT ($p < 0.001$), suggesting that efficient nitrogen allocation to the sheath at this depth significantly contributes to grain number. This finding aligns with previous research emphasizing the importance of nitrogen partitioning to reproductive structures for maximizing yield components [52]. The positive correlations observed for leaf TNTA and GN under all DFBTs further underscore the role of the leaf as a major source of nitrogen for grain filling, supporting the hypothesis that leaf nitrogen content is a critical determinant of grain yield [53].

At the molecular and cellular levels, the role of DFBT in influencing nitrogen dynamics can be linked to changes in the activity of nitrogen transporters, such as nitrate transporters (NRTs) and ammonium transporters (AMTs), which are critical in the uptake and translocation of nitrogen. Under DFBT, the modified soil moisture profile may upregulate the expression of NRT1 and NRT2 gene families in roots, leading to increased nitrate uptake and subsequent allocation to reproductive organs [54]. Similarly, the upregulation of AMT genes under DFBT conditions may facilitate ammonium assimilation, ensuring a steady supply of nitrogen for critical metabolic pathways in the sheath and leaves. This molecular adaptation supports the observation that DFBT at 80 cm optimizes nitrogen use efficiency and contributes to higher GN.

Interestingly, the correlations among TNTA in different organs varied with DFBT depth, indicating differential nitrogen dynamics within the plant. For instance, the negative correlation between the sheath and SAKH TNTA at 80 cm ($p < 0.05$) and 90 cm ($p < 0.01$) depths suggests competitive nitrogen allocation, where increased translocation to the sheath might limit nitrogen availability to the SAKH. This competitive relationship could be a key factor in determining the efficiency of nitrogen use for grain production, as seen in other studies on nutrient partitioning [55]. At the cellular level, this competition could be mediated by the differential activity of nitrogen remobilization enzymes such as glutamine synthetase (GS) and glutamate dehydrogenase (GDH). Enhanced GS activity in the sheath at greater DFBT depths may prioritize nitrogen remobilization to this organ at the expense of SAKH nitrogen translocation, reflecting a trade-off in nitrogen allocation that may influence overall grain production efficiency [56].

The negative correlation between TNTA in the stem and sheath under the control treatment ($p < 0.05$) indicates that in the absence of DFBT, the allocation of nitrogen may be less efficient, potentially leading to suboptimal nitrogen use efficiency. In contrast to the patterns observed under DFBT, a positive correlation was found between the stem TNTA and SAKH TNTA under control conditions ($p < 0.05$), suggesting that nitrogen translocation dynamics are significantly influenced by soil moisture and microenvironmental conditions provided by DFBT [57]. At the molecular level, this differential response could be attributed to hormonal regulation involving cytokinins and abscisic acid (ABA), which are known to mediate nitrogen partitioning in response to environmental stimuli. For example, DFBT may enhance cytokinin synthesis in root tissues, promoting nitrogen mobilization to reproductive organs, while increased ABA levels under drought conditions could inhibit nitrogen allocation to non-essential tissues [58]. These hormonal interactions provide a mechanistic basis for the observed variation in nitrogen translocation under different DFBTs.

The results underscore the importance of DFBT in modulating nitrogen translocation and highlight the complexity of nutrient dynamics within the plant. The differential responses of TNTA in various organs across DFBT depths suggest that optimizing nitrogen use efficiency requires a nuanced understanding of how different soil management practices affect internal nutrient allocation. Future research should prioritize deciphering the molecular mechanisms and signaling pathways, such as the role of nitrogen transporters, remobilization enzymes, and hormone-regulated nitrogen partitioning, that underpin the observed nitrogen dynamics under DFBT. Additionally, integrating advanced omics technologies, such as transcriptomics and metabolomics, could provide deeper insights into the cellular-level adaptations driving nitrogen efficiency and reproductive success in response to varying soil moisture conditions.

4.5. Impact of DFBT on Grain Yield and Nitrogen Content

The observed variations in GY and GN among the different DFBTs highlight the significant influence of soil moisture management on crop performance. The reduced GY under the control and 60 cm DFBTs can be attributed to soil moisture stress, as these conditions likely resulted in inadequate water availability for optimal plant growth. This finding is consistent with previous research indicating that water stress during critical growth periods can severely limit photosynthesis and nutrient uptake, thereby reducing yield [59]. The low GN under these treatments further underscores the negative impact of soil moisture deficits on nitrogen assimilation and grain quality.

Placing FBT at deeper soil layers, such as 100 cm, maximizes water retention but can also lead to waterlogging (Figure 2). This creates anaerobic soil conditions that hinder root respiration and nutrient uptake, ultimately reducing grain yield [60]. Therefore, it is critical to balance adequate soil moisture with effective drainage to maintain optimal crop productivity. Studies suggest that positioning FBT at an intermediate depth, such as 80 cm, achieves this balance, providing sufficient water availability while avoiding excessive retention that causes waterlogging [61,62]. At this depth, the root zone aligns with areas of higher nitrogen availability due to active microbial processes and organic matter decomposition, ensuring adequate oxygen supply and preventing anaerobic conditions [51].

The optimal GY and GN observed at intermediate depths, particularly around 80 cm, further demonstrate the importance of this balance (Figures 2, 4 and 5). This depth promotes favorable root zone conditions, supporting effective water and nutrient uptake, optimal root development, and improved physiological processes critical for grain filling [63]. Additionally, the increased GN at 80 cm highlights enhanced nitrogen use efficiency, a key factor for achieving high yield and superior grain quality. These findings emphasize the need for precise water management strategies tailored to crop water and nutrient requirements at different growth stages [64], optimizing resource utilization for improved productivity and grain quality.

Although this study highlights the significant effects of DFBT on soil moisture retention and nitrogen use efficiency, it lacks an investigation into the dynamic changes in ammonium and nitrate nitrogen within the soil profile. Future research should incorporate soil nitrogen profile monitoring and model simulations to further explore the long-term impacts of different DFBT depths on nitrogen cycling and crop productivity.

5. Conclusions

This 3-year study demonstrates that varying DFBT significantly influences several critical aspects of wheat growth in arid northwest China, including soil moisture retention, TNAA and TNTA, GN, and GY. The results consistently show that an 80 cm DFBT depth provides optimal soil moisture levels, leading to the highest values of TNAA, TNTA, GN, and GY. This specific depth effectively prevents both water stress and waterlogging, which are detrimental to wheat development and productivity, thus highlighting the critical importance of selecting the appropriate DFBT depth to optimize water and nitrogen use efficiency. Consequently, this optimization enhances grain quality and yield. The study also underscores the significant role of nitrogen translocation from nutritive organs, especially leaves, to grains, as a major contributor to final grain nitrogen content. The positive correlations observed between GN, GY, and TNTA in leaves across different DFBTs emphasize the importance of effective nitrogen management in achieving high yields.

In conclusion, this study advocates for the adoption of an 80 cm DFBT depth in wheat cultivation to maximize soil moisture retention, nitrogen utilization, and crop productivity. This study holds significant importance in advancing the understanding of the effects of DFBT on nitrogen dynamics. It demonstrates that DFBT not only improves water retention and nutrient availability but also influences nitrogen metabolism at both physiological and biochemical levels. The findings provide critical insights for developing optimal nitrogen and water management strategies, offering a valuable foundation for achieving higher productivity and sustainability in wheat cultivation under resource-constrained arid environments while addressing the productivity and environmental challenges of modern agriculture. Future research should explore the integration of DFBT with complementary agronomic practices, such as improved irrigation techniques and nutrient management, to enhance overall agricultural sustainability and resilience. This holistic approach is essential for optimizing wheat production in various environmental conditions and ensuring long-term agricultural success.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy15010240/s1, Table S1: Some chemical characteristics of soil (0–100 cm depth) at the experimental site; Table S2: Bulk density of soil and soil moisture status before sowing; Table S3: Soil moisture contents of 0–40 cm depth in different stages of spring wheat growth season in 2014, 2015, and 2016; Table S4: Assessment of economic benefit with different DFBT; Figure S1: Annual temperature and annual rainfall, 2000–2016; Figure S2: Soil moisture contents of 0–40 cm depth in different stages of spring wheat growth season in 2014; Figure S3: Soil moisture contents of 0–40 cm depth in different stages of spring wheat growth season in 2015; Figure S4: Soil moisture contents of 0–40 cm depth in different stages of spring wheat growth season in 2016.

Author Contributions: Z.L.: Conceptualization, software, formal analysis, data curation, and writing—original draft. X.Z. (Xiaolei Zhou): Conceptualization, methodology, formal analysis, investigation, writing—original draft, writing—review and editing, project administration, and funding acquisition; Q.T.: Conceptualization, formal analysis, resources, and writing—review and editing. L.P.S.: Conceptualization, methodology, and writing—review and editing. Y.Y.: Methodology, resources, data curation, and writing—original draft. X.Z. (Xujiao Zhou): Conceptualization, methodology, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Global Environment Facility (GEF) in collaboration with the People's Republic of China (PRC), under the PRC-GEF Foundation Project, grant number GS-GEF/OP12.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Acknowledgments: The authors extend their sincere appreciation to Peter Long (ecologist, New Zealand), and thanks to Su Wanhong, and Sun Hanguo from Jing Tai Control Desert Station in Gansu province for their field assistance.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

FBT	Plastic film-bottomed treatment
DFBT	Depth of film-bottomed treatment
TNAA	Total N absorbability amount
TNTA	Total N translocation amount
GN	Grain N
GY	Grain yield
N	Nitrogen
SAKH	Spike axis and kernel husk
NDF	N derived from fertilizer
NDS	N derived from soil
NUE	nitrogen use efficiency

References

1. Hag Husein, H.; Lucke, B.; Bäumler, R.; Sahwan, W. A Contribution to Soil Fertility Assessment for Arid and Semi-Arid Lands. *Soil Syst.* **2021**, *5*, 42. [CrossRef]

2. Silva, P.C.; Tiritan, C.S.; Echer, F.R.; Cordeiro, C.F.; Rebonatti, M.D.; Santos, C.H. No-tillage and crop rotation increase crop yields and nitrogen stocks in sandy soils under agroclimatic risk. *Field Crops Res.* **2020**, *258*, 107947. [CrossRef]
3. Duivenbooden, N.V.; Pala, M.; Studer, C.; Bielders, C.; Beukes, D.J. Cropping systems and crop complementarity in dryland agriculture to increase soil water use efficiency: A review. *NJAS Wagening. J. Life Sci.* **2000**, *48*, 213–236. [CrossRef]
4. Singh, J.; Kumar, A.; Dhaliwal, A.S. Superabsorbent Polymers Application in Agriculture Sector. In *Properties and Applications of Superabsorbent Polymers*; Arpit, S., Jaya, T., Eds.; Springer: Singapore, 2023. [CrossRef]
5. Batara, B.; Steven, S.; Mulyana, M.; Saputra, A.S.; Hutahaean, A.C.; Yemensia, E.V.; Soekotjo, E.S.; Abidin, A.Z.; Graha, H.P. Recent Advances, Applications, and Challenges in Superabsorbent Polymers to Support Water Sustainability. *J. Appl. Polym. Sci.* 2024; *Early View*. [CrossRef]
6. Coskun, D.; Britto, D.T.; Shi, W.; Kronzucker, H.J. Nitrogen transformations in modern agriculture and the role of biological nitrification inhibition. *Nat. Plants* **2017**, *3*, 17074. [CrossRef]
7. Guo, J.; Jia, Y.; Chen, H.; Zhang, L.; Yang, J.; Zhang, J.; Hu, X.; Ye, X.; Li, Y.; Zhou, Y. Growth, photosynthesis, and nutrient uptake in wheat are affected by differences in nitrogen levels and forms and potassium supply. *Sci Rep.* **2019**, *9*, 1248. [CrossRef]
8. Zhang, T.; Li, Y.; Wu, Q.; Gao, Z. Nitrogen Redistribution and Grain Quality in Wheat. *Cereal Chem.* **2023**, *100*, 55–67. [CrossRef]
9. Nikolenko, O.; Jurado, A.; Borges, A.V.; Knöller, K.; Brouyère, S. Isotopic composition of nitrogen species in groundwater under agricultural areas: A review. *Sci. Total Environ.* **2018**, *621*, 1415–1432. [CrossRef]
10. Yang, W.; Feng, H.; Zhang, X.; Zhang, J.; Doonan, J.H.; Batchelor, W.D.; Xiong, L.; Yan, J. Crop Phenomics and High-Throughput Phenotyping: Past Decades, Current Challenges, and Future Perspectives. *Mol. Plant* **2020**, *13*, 187–214. [CrossRef] [PubMed]
11. Liu, Z.; Cao, S.; Sun, Z.; Wang, H.; Qu, S.; Lei, N.; He, J.; Dong, Q. Tillage effects on soil properties and crop yield after land reclamation. *Sci. Rep.* **2021**, *11*, 4611. [CrossRef] [PubMed]
12. Ahmad, Z.; Waraich, E.A.; Akhtar, S.; Shazia Anjum, S.; Ahmad, T.; Wajid Mahboob, W.; Osama Bin Abdul Hafeez, O.B.A.; Terence Tapera, T.; Maryke Labuschagne, M.; Rizwan, M. Physiological responses of wheat to drought stress and its mitigation approaches. *Acta Physiol Plant.* **2018**, *40*, 80. [CrossRef]
13. Amirahmadi, E.; Ghorbani, M.; Moudrý, J.; Bernas, J.; Mukosha, C.E.; Hoang, T.N. Environmental Assessment of Dryland and Irrigated Winter Wheat Cultivation under Compost Fertilization Strategies. *Plants* **2024**, *13*, 509. [CrossRef] [PubMed]
14. Ravichandran, M.; Samiappan, S.C.; Pandiyan, R.; Velu, R.K. Improvement of Crop and Soil Management Practices through Mulching for Enhancement of Soil Fertility and Environmental Sustainability: A Review. *J. Exp. Biol. Agric. Sci.* **2022**, *10*, 697–712. [CrossRef]
15. Kader, M.A.; Senge, M.; Mojid, M.A.; Ito, K. Recent Advances in Mulching Materials and Methods for Modifying Soil Environment. *Soil Tillage Res.* **2017**, *168*, 155–166. [CrossRef]
16. Araghi, A.R.; Jaghargh, M.R.; Maghrebi, M.; Martinez, C.J.; Fraisse, C.W.; Olesen, J.E.; Hoogenboom, G. Investigation of satellite-related precipitation products for modeling of rainfed wheat production systems. *Agric. Water Manag.* **2021**, *257*, 107222. [CrossRef]
17. Gao, L.; Liu, Q.; Zhang, X.; Wang, J. Increasing Crop Productivity with Film-Bottomed Technology. *Field Crops Res.* **2021**, *275*, 108330. [CrossRef]
18. Kabir, Z.; Koide, R.T. Effect of autumn and winter mycorrhizal cover crops on soil properties, nutrient uptake and yield of sweet corn in Pennsylvania, USA. *Plant Soil* **2002**, *238*, 205–215. [CrossRef]
19. Chen, F.; Zhang, X.; Wang, J.; Li, Y. Integrated Management of Water and Nutrients in Sandy Soils. *Agric. Water Manag.* **2022**, *251*, 106875. [CrossRef]
20. Aydin, G.; Oz, M.T.; Yucel, M.; Oktem, H.A. Cold-Induced Comparative Transcriptome Analysis of Potato (*Solanum tuberosum* L. Cv. Kennebec) That Heterologously Expresses the Rice *Osmyb4* Gene. *J. Biotechnol.* **2016**, *231*, S31. [CrossRef]
21. Ciampitti, I.A.; Makowski, D.; Fernandez, J.; Lacasa, J.; Lemaire, G. Does Water Availability Affect the Critical N Dilution Curves in Crops? A Case Study for Maize, Wheat, and Tall Fescue Crops. *Field Crops Res.* **2021**, *273*, 108301. [CrossRef]
22. Good, A.G.; Beatty, P.H. Fertilizing Nature: A Tragedy of Excess in the Commons. *PLoS Biol.* **2011**, *9*, e1001124. [CrossRef]
23. Zhang, J.; Zhang, S.; Liang, W. Effects of Film-Mulched Furrow Sowing on Soil Water Conservation and Grain Yield of Spring Wheat in an Arid Region. *Field Crops Res.* **2019**, *241*, 107576. [CrossRef]
24. Zhou, X.L.; Wang, H.; Chen, Q.G.; Ren, J.Z. Coupling Effects of Depth of Film-Bottomed Tillage and Amount of Irrigation and Nitrogen Fertilizer on Spring Wheat Yield. *Soil Tillage Res.* **2006**, *94*, 251–261. [CrossRef]
25. Kant, S.; Seneweera, S. Impact of Nitrogen Use Efficiency in Agriculture and the Challenge of Limiting Nitrogen Losses under Climate Change. *Clim. Chang. Agric. Ecosyst.* **2017**, *33*, 33–45.
26. Coelho, E.F.; Lima, L.W.F.; Stringam, B.; De Matos, A.P.; Santos, D.L.; Reinhardt, D.H.; De Melo Velame, L.; Dos Santos, C.E.M.; Da Cunha, F.F. Water Productivity in Pineapple (*Ananas comosus*) Cultivation Using Plastic Film to Reduce Evaporation and Percolation. *Agric. Water Manag.* **2024**, *296*, 108785. [CrossRef]
27. Singh, P.; Kumar, R. Evapotranspiration from Wheat under a Semi-Arid Climate and a Shallow Water Table. *Agric. Water Manag.* **1993**, *23*, 91–108. [CrossRef]

28. Cai, J.B.; Liu, Y.; Zhou, J.C. Research on Crop Water Requirement and Irrigation Procedure in Jingtai Pumping Irrigation District of Gansu Province. *J. Chin. Country Water Electr.* **2003**, *8*, 35–39.
29. Mogensen, V.O.; Jensen, H.E.; Rab, M.A. Grain Yield, Yield Components, Drought Sensitivity, and Water Use Efficiency of Spring Wheat Subjected to Water Stress at Various Growth Stages. *Irrig. Sci.* **1985**, *6*, 131–140. [CrossRef]
30. Budak, H.; Kantar, M.; Kurtoglu, K.Y. Drought Tolerance in Modern and Wild Wheat. *Sci. World J.* **2013**, 548246. [CrossRef] [PubMed]
31. Brown, B. Water Management with Reduced Supplies. *Cereal Sentin.* **2001**, *26*, 2–4.
32. Gardner, W.H. Water Content. In *Methods of Soil Analysis Part 1 Physical and Mineralogical Methods*; Klute, A., Ed.; ASA and SSSA: Madison, WI, USA, 1986; pp. 635–662.
33. Chatterjee, A.; Acharya, U. Relationship among Different Soil Biochemical Methods to Determine Soil Health. *Open J. Soil Sci.* **2018**, *8*, 303–313. [CrossRef]
34. Arora, A.; Singh, V.P.; Mohan, J. Effects of Nitrogen and Water Stress on Photosynthesis and Nitrogen Content in Wheat. *Biol. Plant* **2001**, *44*, 153–155. [CrossRef]
35. Chalk, P.M.; Magalhães, A.M.T.; Urquiaga, S. Integrated Effects of Abiotic Stresses on Inoculant Rhizobia and Host Legume Performance Using 15N Techniques. *Field Crops Res.* **2006**, *96*, 263–278. [CrossRef]
36. Ledgard, S.F.; Freney, J.R. ^{15}N for Field Use. *Fertil. Res.* **1992**, *31*, 341–349. [CrossRef]
37. Robinson, D. δ^{15}N as an Integrator of the Nitrogen Cycle. *Trends Ecol. Evol.* **2001**, *16*, 153–162. [CrossRef] [PubMed]
38. Jamieson, P.D.; Semenov, M.A. Modelling Nitrogen Uptake and Redistribution in Wheat. *Field Crops Res.* **2000**, *68*, 21–29. [CrossRef]
39. SAS Institute Inc. *SAS/STAT 14.3 User's Guide*; SAS Institute Inc.: Cary, NC, USA, 2018.
40. Thakur, M.; Kumar, R. Mulching: Boosting Crop Productivity and Improving Soil Environment in Herbal Plants. *J. Appl. Res. Med. Aromat. Plants* **2021**, *20*, 100287. [CrossRef]
41. Çolak, Y.B.; Yazar, A.; Çolak, İ.; Akça, H.; Duraktekin, G. Evaluation of Crop Water Stress Index (CWSI) for Eggplant under Varying Irrigation Regimes Using Surface and Subsurface Drip Systems. *Agric. Agric. Sci. Procedia* **2015**, *4*, 372–382. [CrossRef]
42. Hoover, D.L.; Pfennigwerth, A.A.; Duniway, M.C. Drought Resistance and Resilience: The Role of Soil Moisture–Plant Interactions and Legacies in a Dryland Ecosystem. *J. Ecol.* **2021**, *109*, 3280–3294. [CrossRef]
43. Kader, M.A.; Singha, A.; Begum, M.A.; Jewel, A.; Khan, F.H.; Khan, N.I. Mulching as water-saving technique in dryland agriculture: Review article. *Bull. Natl. Res. Cent.* **2019**, *43*, 147. [CrossRef]
44. Sağlam, M.; Selvi, K.Ç.; Dengiz, O.; Gürsoy, F.E. Affects of different tillage managements on soil physical quality in a clayey soil. *Environ Monit Assess.* **2015**, *187*, 4185. [CrossRef]
45. Lu, H.; Xia, Z.; Fu, Y.; Wang, Q.; Xue, J.; Chu, J. Response of Soil Temperature, Moisture, and Spring Maize (*Zea mays* L.) Root/Shoot Growth to Different Mulching Materials in Semi-Arid Areas of Northwest China. *Agronomy* **2020**, *10*, 453. [CrossRef]
46. Adeboye, O.B.; Schultz, B.; Adekalu, K.O.; Prasad, K. Soil water storage, yield, water productivity and transpiration efficiency of soybeans (*Glyxine max* L. Merr) as affected by soil surface management in Ile-Ife, Nigeria. *Int. Soil Water Conserv. Res.* **2017**, *5*, 141. [CrossRef]
47. Adhikari, R.; Bristow, K.L.; Casey, P.S.; Freischmidt, G.; Hornbuckle, J.W.; Adhikari, B. Preformed and sprayable polymeric mulch film to improve agricultural water use efficiency. *Agric. Water Manag.* **2016**, *169*, 1–13. [CrossRef]
48. Chakraborty, D.; Nagarajan, S.; Aggarwal, P.; Gupta, V.K.; Tomar, R.K.; Garg, R.N.; Sahoo, R.N.; Sarkar, A.; Chopra, U.K.; Sarma, K.S.S.; et al. Effect of mulching on soil and plant water status, and the growth and yield of wheat (*Triticum aestivum* L.) in a semi-arid environment. *Agric. Water Manag.* **2008**, *95*, 1323–1334. [CrossRef]
49. Zhang, L.; Liu, H.; Wang, M. Impact of Different Mulching Depths on Nitrogen Dynamics and Crop Yield. *Agric. Syst.* **2021**, *187*, 103026. [CrossRef]
50. Qin, W.; Hu, C.; Oenema, O. Soil Mulching Significantly Enhances Yields and Water and Nitrogen Use Efficiencies of Maize and Wheat: A Meta-Analysis. *Sci. Rep.* **2015**, *5*, 16210. [CrossRef]
51. Wang, J.; Fan, Z.; Zhao, Y. Nitrogen Translocation and Partitioning in Crops under Different Soil Moisture Regimes. *Agric. Water Manag.* **2021**, *246*, 106664. [CrossRef]
52. Ghimire, D.; Das, S.; Mueller, N.D.; Creech, C.F.; Santra, D.; Baenziger, P.S.; Easterly, A.C.; Maust, B.; Maharjan, B. Effects of Cultivars and Nitrogen Management on Wheat Grain Yield and Protein. *Agron. J.* **2021**, *113*, 4348–4368. [CrossRef]
53. Martre, P.; Porter, J.R.; Jamieson, P.D.; Triboi, E. Modelling grain nitrogen accumulation and protein composition to understand the sink/source regulations of nitrogen remobilization for wheat. *Plant Physiol.* **2007**, *143*, 78–95. [CrossRef]
54. Jackson, L.E.; Burger, M.; Cavagnaro, T.R. Roots, Nitrogen Transformations, and Ecosystem Services. *Annu. Rev. Plant Biol.* **2008**, *59*, 341–363. [CrossRef] [PubMed]
55. Barbottin, A.; Lecomte, C.; Bouchard, C.; Jeuffroy, M.H. Nitrogen Remobilization during Grain Filling in Wheat: Genotypic and Environmental Effects. *Crop Sci.* **2005**, *45*, 1141–1150. [CrossRef]

56. Masclaux-Daubresse, C.; Daniel-Vedele, F.; Dechorgnat, J.; Chardon, F.; Gaufichon, L.; Suzuki, A. Nitrogen uptake, assimilation and remobilization in plants: Challenges for sustainable and productive agriculture. *Ann. Bot.* **2010**, *105*, 1141–1157. [CrossRef]
57. Sinclair, T.R.; Jamieson, P.D. Yield and Grain Number of Wheat: A Correlated Response. *Field Crops Res.* **2008**, *105*, 169–173. [CrossRef]
58. Sakakibara, H.; Takei, K.; Hirose, N. Interactions between nitrogen and cytokinin in the regulation of metabolism and development. *Trends Plant Sci.* **2006**, *11*, 440–448. [CrossRef] [PubMed]
59. Passioura, J.B. Phenotyping for Drought Tolerance in Grain Crops: When Is It Useful to Breeders? *Funct. Plant Biol.* **2012**, *39*, 851–859. [CrossRef] [PubMed]
60. Islam, M.R.; Hasan, M.; Akter, M.; Shibly, N.N. Post-Waterlogging Rescue Nitrogen Improves Waterlogging Tolerance in Mungbean (*Vigna radiata*). *Agriculturists* **2019**, *17*, 1–13. [CrossRef]
61. Abdelhak, M. Soil Improvement in Arid and Semiarid Regions for Sustainable Development. In *Natural Resources Conservation and Advances for Sustainability*; Jhariya, M.K., Meena, R.S., Banerjee, A., Meena, S.N., Eds.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 73–90, ISBN 978-0-12-822976-7.
62. Islam, M.; Guo, Z.; Jiang, F. Does Straw Return Increase Crop Yield in the Wheat-Maize Cropping System in China? A Meta-Analysis. *Field Crops Res.* **2022**, *279*, 108447. [CrossRef]
63. Xu, G.; Fan, X.; Miller, A.J. Plant Nitrogen Assimilation and Use Efficiency. *Annu. Rev. Plant Biol.* **2012**, *63*, 153–182. [CrossRef] [PubMed]
64. Kang, S.; Zhang, L.; Liang, Y. Effects of Limited Irrigation on Yield and Water Use Efficiency of Wheat and Maize in a Semi-Arid Region. *Agric. Water Manag.* **2002**, *55*, 203–216. [CrossRef]