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# Resource Use Efficiencies of $C_3$ and $C_4$ Cereals under Split Nitrogen Regimes

**Zartash Fatima [1], Qaiser Abbas [1], Amna Khan [1], Sajjad Hussain [1], Muhammad Arif Ali [1], Ghulam Abbas [1], Haseeb Younis [1], Shahrish Naz [1], Muhammad Ismail [1], Muhammad Imran Shahzad [1], Muhammad Nadeem [1], Umair Farooq [1], Shahzad Usman Khan [1], Kashif Javed [1], Azhar Ali Khan [2], Mukhtar Ahmed [3], Muhammad Azam Khan [4] and Shakeel Ahmad [1,*]**

[1] Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan 60800, Pakistan; zartashfatima15@yahoo.com (Z.F.); qaisermultan@gmail.com (Q.A.); amnaazamkhan@yahoo.com (A.K.); sajjad.hussain@bzu.edu.pk (S.H.); arif1056@bzu.edu.pk (M.A.A.); maharabbastarar@gmail.com (G.A.); haseebyounis99@gmail.com (H.Y.); sahrishnaz.agronomist@gmail.com (S.N.); muhammadismail@yahoo.com (M.I.); muhammadimranshahzad@yahoo.com (M.I.S.); nadeembhatti956@gmail.com (M.N.); umair_73@yahoo.com (U.F.); shahzadusmankhan99@gmail.com (S.U.K.); kashif.javed@pioneer.com (K.J.)
[2] PARC, Research and Training Station, Bahauddin Zakariya University, Multan 60800, Pakistan; azharalikhan@yahoo.com
[3] PMAS, Arid Agriculture University, Rawalpindi 46300, Pakistan; ahmadmukhtar@uaar.edu.pk
[4] In-service Agriculture Training Institute, Sargodha 40100, Pakistan; muhammadazamkhan@yahoo.com
* Correspondence: shakeelahmad@bzu.edu.pk; Tel.: +92-300-731-8911

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**Abstract:** Resources are limited, thus improving resource use efficiency is a key objective for cereal-based cropping systems. This field study was carried out to quantify resource use efficiencies in selected $C_3$ and $C_4$ cereals under split nitrogen (N) application regimes. The study included the following treatments: six cereals (three $C_3$: wheat, oat, and barley; and three $C_4$: maize, millet, and sorghum) and four split N application regimes ($NS_1$ = full amount of N at sowing; $NS_2$ = half N at sowing + half N at first irrigation; $NS_3 = \frac{1}{3}$ N at sowing + $\frac{1}{3}$ N at first irrigation + $\frac{1}{3}$ N at second irrigation; $NS_4 = \frac{1}{4}$ N at sowing + $\frac{1}{4}$ N at first irrigation + $\frac{1}{4}$ N at second irrigation + $\frac{1}{4}$ N at third irrigation). Results revealed that $C_4$ cereals out-yielded $C_3$ cereals in terms of biomass production, grain yield, and resource use efficiencies (i.e., radiation use efficiency (RUE) and nitrogen use efficiency (NUE)), while splitting N into three applications proved to be a better strategy for all of the selected winter and summer cereals. The results suggest that $C_4$ cereals should be added into existing cereal-based cropping systems and N application done in three installments to boost productivity and higher resource use efficiency to ensure food security for the burgeoning population.

**Keywords:** barley; maize; millet; oat; radiation use efficiency; sorghum; wheat

## 1. Introduction

Cereals constitute a large proportion of food supplements. These are used in diets as end-products and provide greater than 70% of the worldwide caloric intake. Wheat (*Triticum aestivum* L.), oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.), maize (*Zea mays* L.), millet (*Pennisetum americanum* L.), and sorghum (*Sorghum bicolor* L.) are the main $C_3$ winter and $C_4$ summer cereals being grown in Asia [1–4]. The classification and physiological characteristics of cereals are presented in Table 1 [5]. The historical area and production of first-, second-, and third-order cereals in Pakistan is presented in Figure 1 [6]. Currently, productivity and resource use efficiency of $C_3$ winter and $C_4$ summer cereals are low in Pakistan compared to other countries in the region [7–17], indicating a substantial potential to increase resource use efficiencies [6,18–26].

**Table 1.** Classification of commonly grown $C_3$ and $C_4$ cereal crops in Asia.

| **Crop/Botanical Name** | **Family** | **Life cycle** | **Season** | **Photoperiod** | **Growth habit** | **Pollination** | **Propagation** | **Photosynthesis** | **Nutrient uptake** | **Root system** |
|---|---|---|---|---|---|---|---|---|---|---|
| Wheat (*Triticum aestivum* L.) | Poaceae | Annual | Winter | Long-day | Determinate | Self-pollinated | Seed | $C_3$ | Exhaustive | Fibrous |
| Oat (*Avena sativa* L.) | | | | | | | | | | |
| Barley (*Hordeum vulgare* L.) | | | | | | | | | | |
| Maize (*Zea mays* L.) | | | Summer | Day-neutral | | Cross-pollinated | | $C_4$ | | |
| Millet (*Pennisetum americanum* L.) | | | | Short-day | | | | | | |
| Sorghum (*Sorghum bicolor* L.) | | | | | | Self-pollinated | | | | |
| Rice (*Oryza sativa* L.) | | | | | | | | $C_3$ | | |

Source: Nazir et al. [5].

The world nitrogen-use efficiency (NUE) for cereal production is around 33% [27,28]. Reported N losses (Figure 2) are presented in Table 2 [29–38]. Lower production is due to the meager use of all available resources along with climate variability and change [3,39–42]. Paradoxically, growers growing $C_3$ and $C_4$ cereals adopt conventional practices instead of approved practices that make more efficient use of resources [43–50]. Nitrogen is the key constituent of agricultural inputs to maintain production of these cereals throughout their lifecycle [51–54] (Figure 3). Surplus N and/or N applied without splitting can be lost through pathways such as nitrification and volatilization [8,40,41] (Figure 1). Principally, it is essential to boost NUE through better approaches to increase RUE. So, split N application regimes result in considerable boost in NUE, production, and resultantly RUE by reducing losses and improving uptake [41]. It is a rising concern that most of the available or applied N is lost, thereby reducing NUE, which is just 29% for cereals in developing agrarian economies [55,56]. This research study was carried out to validate the influence of split N application on biomass accumulation, grain yields, and resource use efficiencies such as NUE and RUE for $C_3$ winter and $C_4$ summer cereals.

**Table 2.** Losses of N fertilizer in cereal crops.

| **N losses** | **Loss (%)** | **Crop/Condition** | **Reference** |
|---|---|---|---|
| Nitrate | 52–73 | Corn | [30] |
| | >21 | Winter wheat | [31] |
| Denitrification | 9.5 | Winter wheat | [32] |
| | 10 | Rice | [33] |
| | >10 | Corn | [34] |
| Runoff | 1–13 | | [35,36] |
| Volatilization | 40 | Without incorporated | [37,38] |
| Drainage | 23 | Tile | [39] |

Source: Raun et al. [28].

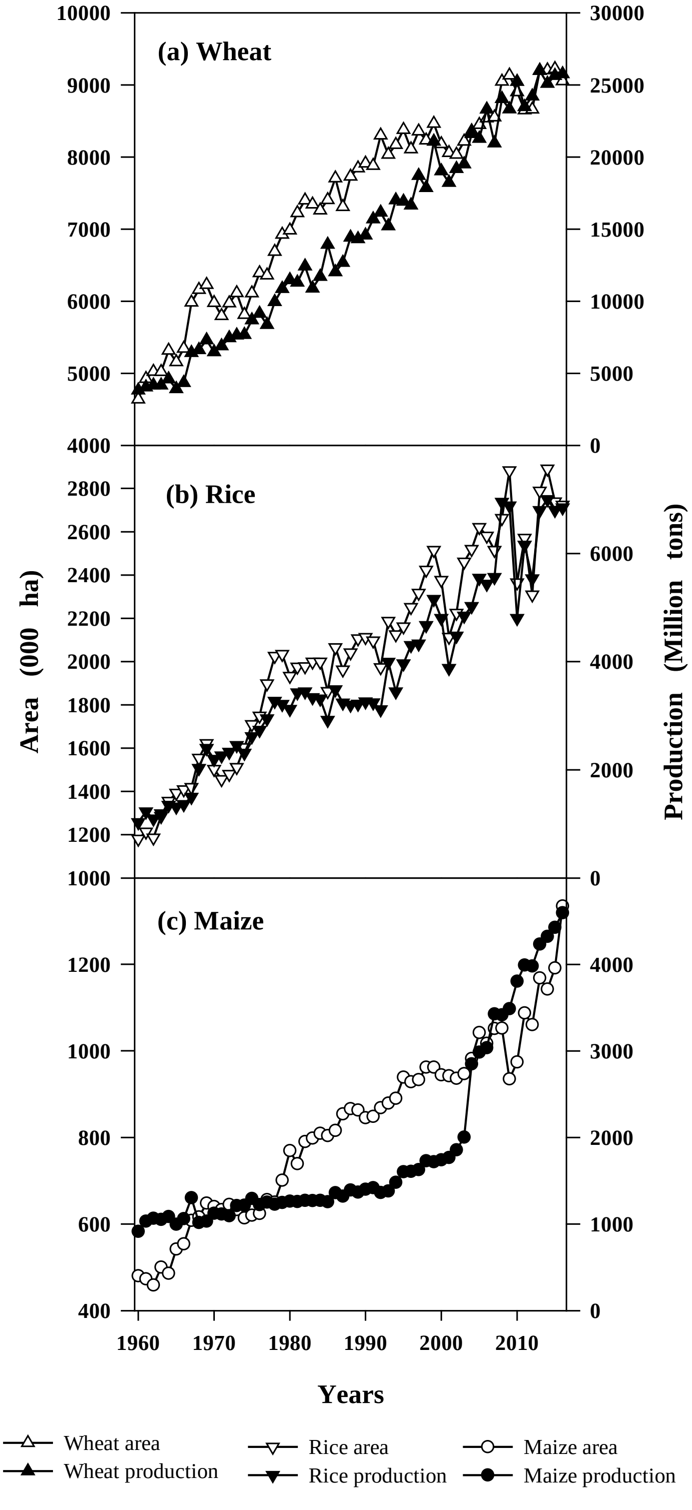

**Figure 1.** Wheat, rice, and maize area and production in Pakistan from 1960 to 2016. Source: Government of Pakistan [7].

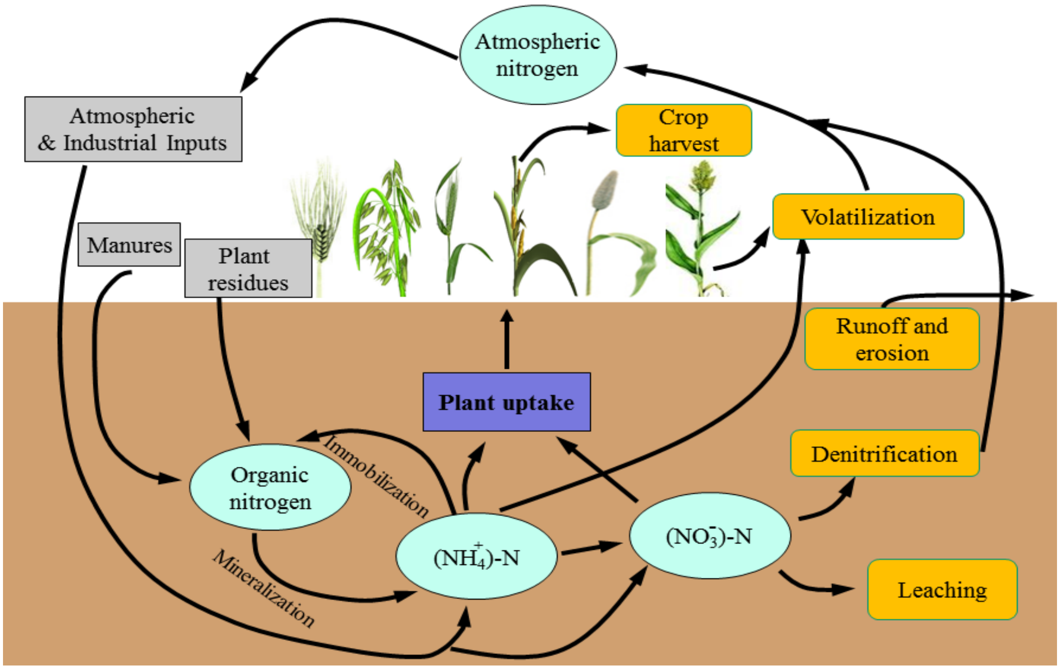

**Figure 2.** Generalized N cycle representing different inputs, losses, and plant uptakes for $C_3$ and $C_4$ cereal crops.

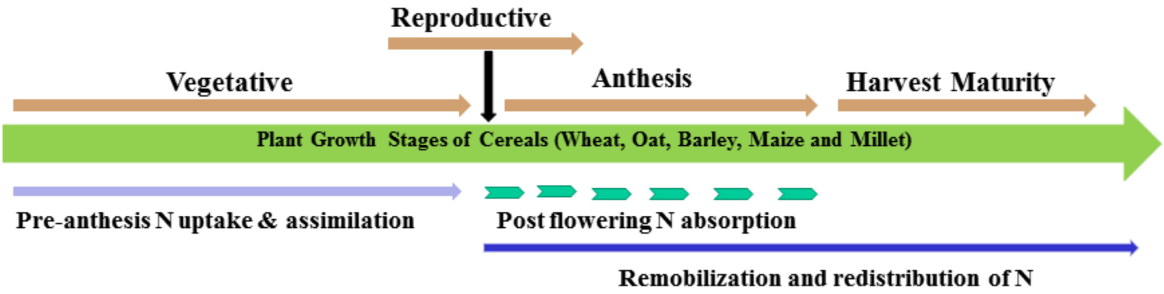

**Figure 3.** A simplistic schematic chart of N in $C_3$ and $C_4$ cereal crop plants representing different transformations that occur during the life span from sowing to harvesting of $C_3$ and $C_4$ cereal crops. The N uptake, absorption, remobilization, and redistribution are represented with different lines in relation to various growth stages. (Source: Modified and adapted from [54].)

## 2. Materials and Methods

### 2.1. Site and Experiment Description

Research experiments were carried out at the Agronomic Research Area at Bahauddin Zakariya University, Pakistan (30°15′ N latitude, 71°30′ E longitude, and 126.6 m a.s.l.). The research site was situated under irrigated conditions in an arid environment of a silt clay loam textural class. The detailed description of the physical and chemical features of the soil has been published previously [1,10]. The meteorological conditions for $C_3$ winter and $C_4$ summer cereal seasons are presented in Figure 4, and the treatments and experimental details are outlined in Table 3. There were three replications and net plot size has been mentioned in Table 3.

**Table 3.** Agronomic practices for $C_3$ winter (wheat, oat, and barley) and $C_4$ summer (maize, millet, and sorghum) cereals.

| **Crops/Cultural Practices** | **Wheat** | **Oat** | **Barley** | **Maize** | **Millet** | **Sorghum** |
|---|---|---|---|---|---|---|
| | **$C_3$ Cereals** | | | **$C_4$ Cereals** | | |
| Sowing date | November 14 | | | August 18 | | |
| N (kg ha$^{-1}$) | 125 | 115 | 50 | 227 | 170 | 100 |
| Irrigations | December 7, January 14, February 1, March 11 | | | September 12, September 28, October 17, October 31 | | |
| Fertilizer dates | November 14, December 10, January 17, February 3 | | | August 18, September 12, September 28, October 31 | | |
| Split N treatments | $NS_1$ = whole N at sowing; $NS_2$ = $\frac{1}{2}$ N at sowing + $\frac{1}{2}$ N at first irrigation; $NS_3$ = $\frac{1}{3}$ N at sowing + $\frac{1}{3}$ N at first irrigation + $\frac{1}{3}$ N at second irrigation; $NS_4$ = $\frac{1}{4}$ N at sowing + $\frac{1}{4}$ N at first irrigation + $\frac{1}{4}$ N at second irrigation + $\frac{1}{4}$ N at third irrigation | | | | | |
| Net plot size | 2 m × 5 m | 2 m × 5 m | 2 m × 5 m | 8 m × 10 m | 6 m × 10 m | 3.5 m × 10 m |
| Soil properties | Sand 28%, silt 52%, and clay 20%, pH 9.6, EC 3.42 ds m$^{-1}$, OM 0.74%, total N 0.033%, P 4.92 ppm, and K 255 ppm | | | pH 8.02, EC 2.3 ds m$^{-1}$, $C_{org}$ 0.76%, $N_{tot}$ 0.039%, $P_{Olsen}$ 5.1 mg kg$^{-1}$, and $K_{ext}$ 110 mg kg$^{-1}$ | | |
| Harvest date | 24 April | 26 April | 22 April | 11 December | 6 December | 14 December |

EC = Electrical conductivity; OM = Organic matter; $N_{tot}$ = Nitrogen total; $P_{Olsen}$ = Phosphorus Olsen; $K_{ext}$ = Potassium extractable.

### 2.2. Data Collection

Common techniques were employed to record growth data. The leaf-area index (LAI) of a sample (10 g) of fully expanded fresh leaves for $C_3$ winter and $C_4$ summer cereal crops were taken, and leaf-area was recorded by means of a leaf-area meter. LAI was recorded using the methodology of Watson [57].

$$\text{LAI}_{\text{(C3, C4 Cereals)}} = \text{Leaf area}_{\text{(C3, C4 Cereals)}} / \text{Land area}_{\text{(C3, C4 Cereals)}} \quad (1)$$

The RUE was computed for $C_3$ winter and $C_4$ summer cereal crops as follows:

$$\text{RUE}_{\text{TDM (C3, C4 Cereals)}} = \text{TDM}\left(_{\text{C3, C4 Cereals}}\right) / \sum \text{Sa}\left(_{\text{C3, C4 Cereals}}\right) \quad (2)$$

where $\sum$Sa is the cumulative photosynthetically active radiation PAR for $C_3$ winter and $C_4$ summer cereal crops that was anticipated to be half of the total daily instance radiation, and TDM is total aboveground biomass [58] and calculated using the following equation:

$$\text{Sa}\left(_{\text{C3, C4 Cereals}}\right) = \text{F}_\text{i}\left(_{\text{C3, C4 Cereals}}\right) \times \text{S}_\text{i}\left(_{\text{C3, C4 Cereals}}\right) \quad (3)$$

where $S_i$ is the incident PAR for $C_3$ winter and $C_4$ summer cereal crops, and $F_i$ was appraised from corresponding cereal crop LAIs by means of the Monteith and Elston [59] equation.

$$\text{F}_\text{i}\left(_{\text{C3, C4 Cereals}}\right) = 1 - \exp\left(-\text{k}_{\text{(C3, C4 Cereals)}} \times \text{LAI}_{\text{(C3, C4 Cereals)}}\right) \quad (4)$$

where $F_i$ is the fraction of intercepted radiation, k is an extinction coefficient for the total solar radiation, and the LAI is for $C_3$ winter and $C_4$ summer cereal crops [60]. The standards of k for wheat, oat, barley, maize, sorghum, and millet were 0.70, 0.63, 0.74, 0.65, 0.63, and 0.52, respectively [61–64]. Multiplying the totals by proper estimates of Fi plus Si produced the quantity of intercepted radiation (Sa) for $C_3$ winter plus $C_4$ summer cereals.

The NUE was calculated as the ratio of grain yield (GY) to quantity of N application [1,10,65]:

$$\text{NUE}_{\text{(C3, C4 Cereals)}} = \text{Grain yield}\left(\text{N}_{\text{X (C3, C4 Cereals)}}\right) / \text{N application rate}_{\text{(C3, C4 Cereals)}} \quad (5)$$

### 2.3. Statistical Analysis

Data thus collected after field experiments were analyzed by Statistix 8.1 (Tallahassee, FL, USA) for ANOVA. Treatment differences were addressed through the methodology of Steel et al. [66].

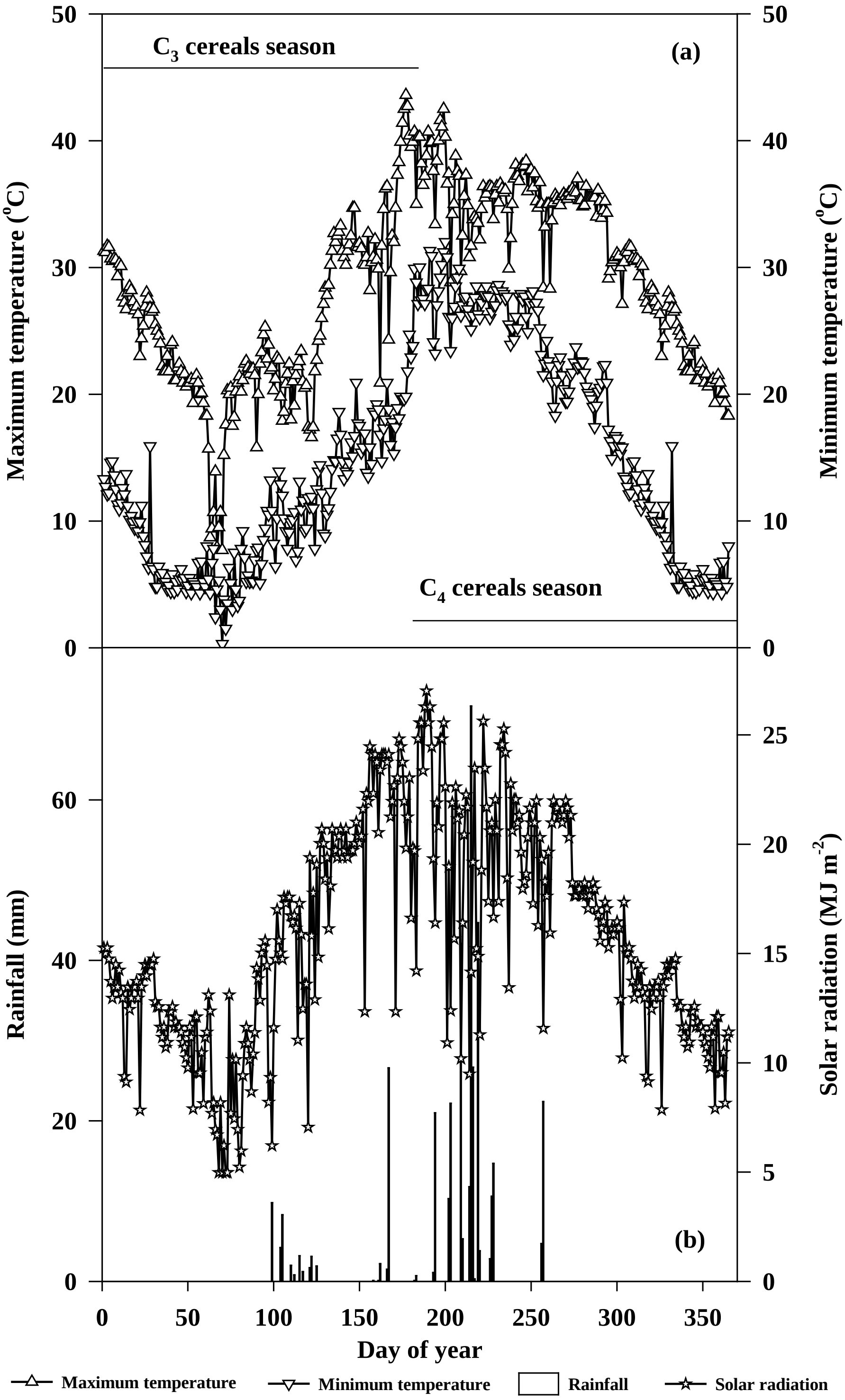

**Figure 4.** (**a**) Daily maximum (upward triangles) and minimum (downward triangles) temperatures, precipitation (unfilled bars), and solar radiation (unfilled stars) (**b**) during $C_3$ and $C_4$ cereal seasons (represented by lines) at Multan, Pakistan.

## 3. Results

### 3.1. Biomass

Seasonal differential accumulation of biomass occurred throughout the life cycle (including vegetative and reproductive stages till maturity) in all $C_3$ winter and $C_4$ summer cereals (Figure 5). Almost half of the biomass was accumulated till anthesis by all the $C_3$ and $C_4$ cereal crops. Overall, $C_4$ cereals performed better than $C_3$ cereals. Across winter and summer cereals and split N regimes, average biomass varied from 425 to 703 g/m$^2$ and 1083 to 1660 g/m$^2$ among $C_3$ and $C_4$ cereals, respectively (Figure 5). Among these cereals, wheat and maize produced higher biomass compared to other $C_3$ and $C_4$ crops, respectively. The biomass productivity of these cereal crops was higher when N was applied in three equal doses compared to other regimes. The lowest biomass was recorded when N was applied in four splits. These selected $C_3$ winter and $C_4$ summer cereals reached peak LAI just before the anthesis stage, which varied substantially among crops and split N application regimes (statistics not given).

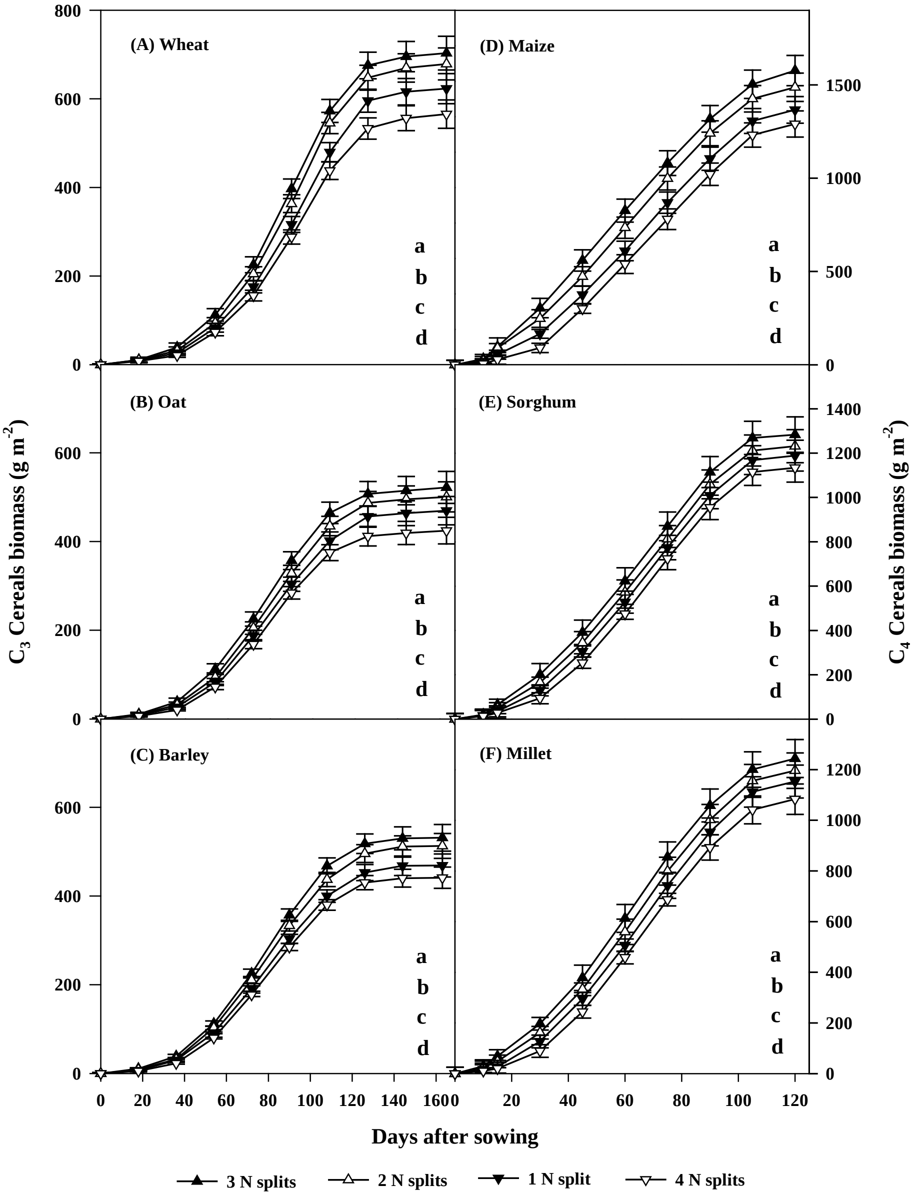

**Figure 5.** Total biomass production of winter $C_3$ (**A**–**C**) and summer $C_4$ (**D**–**F**) cereals under split N application regimes. Bars and letters represent standard error and significance, respectively.

### 3.2. Grain Yield (GY)

The data for GY for these winter and summer cereals significantly differed among crops with split N application regimes (Figure 6). Overall, GY ranged from 198 to 883 g/m$^2$ in the case of cereals and split N application regimes. The $C_4$ cereals also out-yielded $C_3$ in terms of GY, and it varied from 198 to 338 g/m$^2$ and 205 to 883 g/m$^2$ for the $C_3$ winter and $C_4$ summer cereals, respectively. Among winter and summer cereal wheat (338 g/m$^2$) and maize (883 g/m$^2$), crops produced higher GY, respectively, compared to other cereal crops. However, in all $C_3$ winter and $C_4$ summer cereals, higher GY was recorded when N was applied in three splits compared to other regimes. The lowest GY was observed for oat (198 to 253 g/m$^2$) and millet (205 to 266 g/m$^2$) crops. Among N application regimes, the lowest GY was recorded when N was applied in four splits.

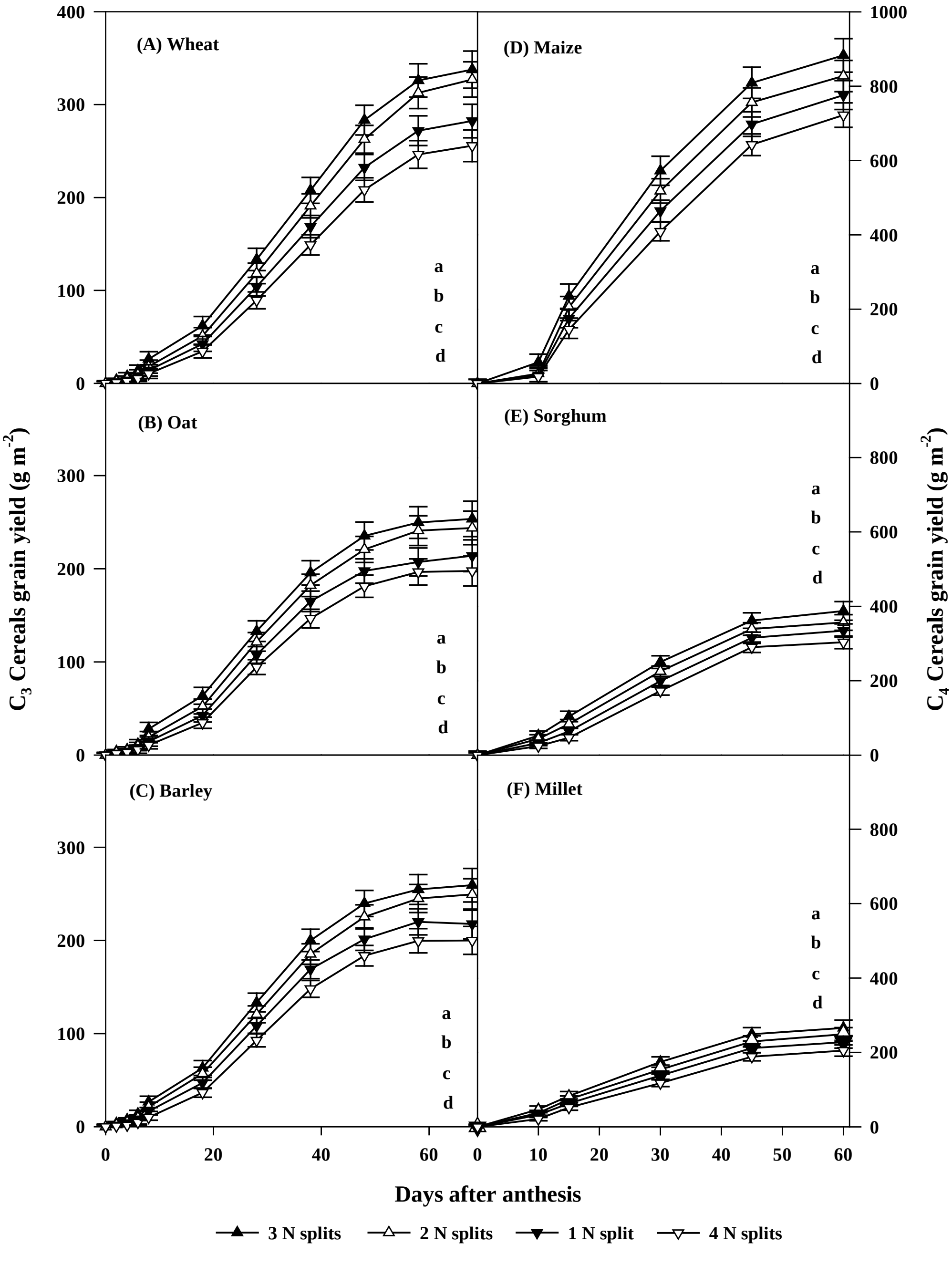

**Figure 6.** Grain yield of winter $C_3$ (**A**–**C**) and summer $C_4$ (**D**–**F**) cereals under split N application regimes. Bars and letters represent standard error and significance, respectively.

### *3.3. Radiation Use Efficiency (RUE)*

The RUE for wheat, oat, barley, maize, sorghum, and millet crops and split N application regimes significantly differed (Figure 7). Overall, among all these cereal crops, $C_4$ summer cereals also out-yielded $C_3$ winter cereals in terms of capturing photosynthetically active radiation. The RUE varied from 0.90 to 1.42 g $MJ^{-1}$ and 1.95 to 2.31 g $MJ^{-1}$ in the case of $C_3$ and $C_4$ cereals, respectively. Among split N application regimes, the maximum RUE (2.31 g $MJ^{-1}$) was found in the treatment where N was applied in three splits, and the lowest (0.90 g $MJ^{-1}$) was recorded for the four splits condition.

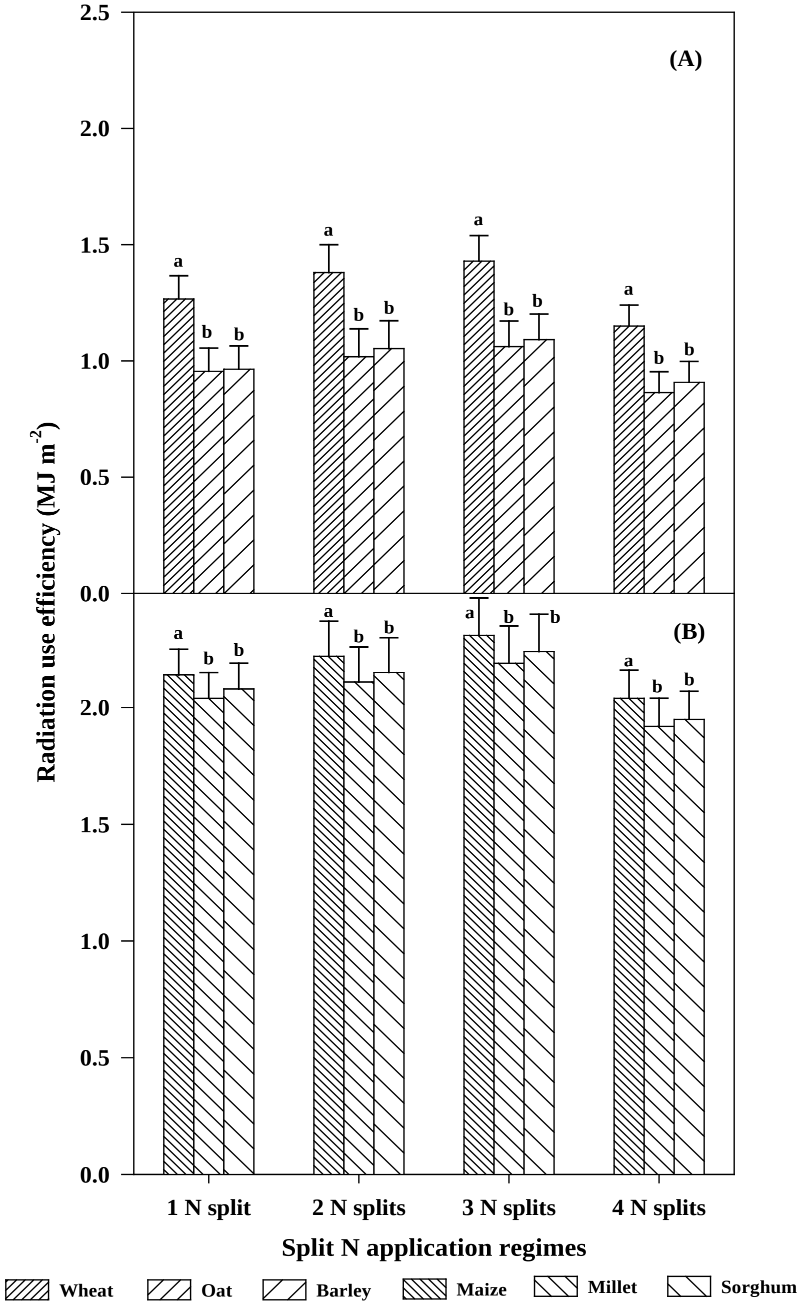

**Figure 7.** Radiation use efficiency of $C_3$ winter ((**A**) wheat, oat, and barley) and $C_4$ summer ((**B**) maize, millet, and sorghum) cereals under split N application regimes. Bars represent standard error.

### *3.4. Nitrogen Use Efficiency (NUE)*

The NUE for $C_3$ (wheat, oat, barley) and $C_4$ (maize, millet, sorghum) cereal crops and split N application regimes differed significantly (Figure 8). Overall, among all these cereal crops, $C_4$ summer cereals also out-yielded $C_3$ winter cereals in terms of NUE, varying from 17.84 to 38.88 kg kg$^{-1}$ and 17.18 to 51.86 kg kg$^{-1}$ in the case of $C_3$ plus $C_4$ cereals. Among split N application regimes, the highest NUE (51.86 kg kg$^{-1}$) was found in the treatment where N was applied in three splits, while the lowest (17.84 kg kg$^{-1}$) was recorded for four splits. The 1:1 lines between the RUE and NUE of $C_3$ and $C_4$ cereals are presented in Figure 9.

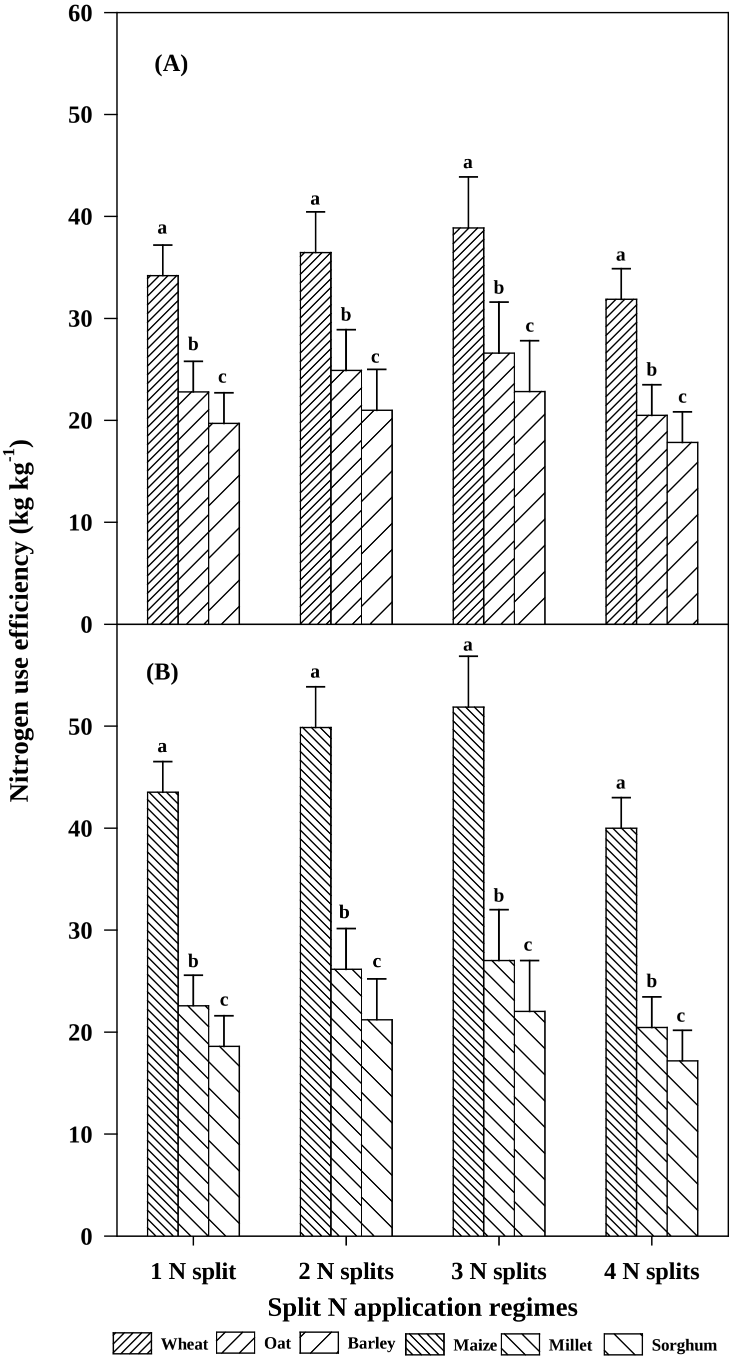

**Figure 8.** Nitrogen use efficiency (NUE) of $C_3$ winter ((**A**) wheat, oat, and barley) and $C_4$ summer ((**B**) maize, millet, and sorghum) cereals under split N application regimes. Bars represent standard error.

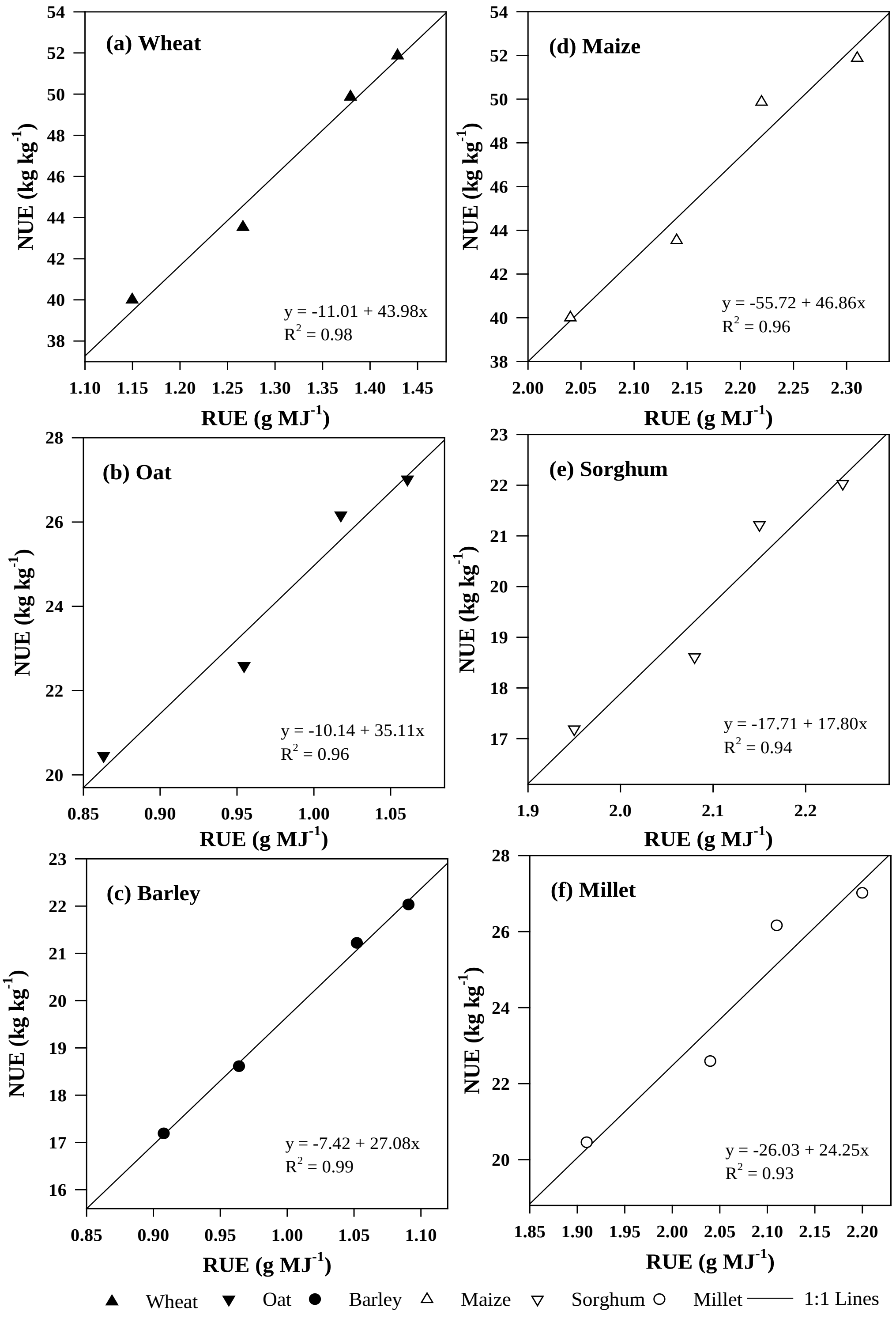

**Figure 9.** Relationship between RUE and NUE of $C_3$ winter (**a**–**c**) and $C_4$ summer (**d**–**f**) cereals at Multan, Pakistan.

## 4. Discussion

$C_4$ summer cereals (maize, millet, and sorghum) having $C_4$ carbon metabolism were found to be superior in accumulating biomass to $C_3$ winter cereals at different split N application regimes. The $C_4$ cereals produce higher biomass and grain yields as compared to $C_3$ cereal crops. This variation for biomass and grain yield was possibly due to the supremacy of $C_4$ cereals as compared to $C_3$ cereal crops towards harnessing higher resource use efficiencies for N [67,68].

The N application in three splits proved to be an effective strategy for all six $C_4$ and $C_3$ cereal crops as compared to other split application regimes. N application at sowing without splitting likely increases the losses through volatilization, nitrification, denitrification, and leaching (Figure 1). However, N application in four splits creates hidden hunger and did not fulfil the optimum nutrient requirements of all $C_4$ and $C_3$ summer and winter cereals during the crop lifetime. This deficiency is reflected in the form of low biomass, grain yields, NUE, and RUE in this study as well as elsewhere [69,70].

Growth dilution effect with variations in N in $C_4$ and $C_3$ cereal crops necessitate the splitting of N. The N is directly linked with leaf photosynthesis as well as higher NUE [40,71]. Variation in N dynamics as well as NUE has substantial effects on photosynthetic efficiency and growth [72].

In this study, $C_4$ summer cereals out-yielded $C_3$ winter cereal in terms of RUE and NUE. The RUE and NUE varied from 0.90 to 2.31 g $MJ^{-1}$ and 17.84 to 51.86 kg $kg^{-1}$ for the $C_3$ and $C_4$ cereals. Among split N application regimes, the highest RUE and NUE were found in the treatment in which N was applied in three splits, possibly due to the continuous and optimum availability of resources. It is a well-established fact that at optimum availability of N, the RUE of $C_3$ and $C_4$ cereals is enhanced, producing more height, LAI, light interception, and canopy development [1,10,73–75]. Similar trends of RUE against applied N in $C_4$ cereals indicated that RUE might be even somewhat better on a total biomass basis. The $C_4$ cereals displayed additional LAI compared to $C_3$. Conversely, it seems inadequate for $C_3$ cereals to accrue leaf N to obtain the level of $C_4$ cereals. Splitting N approach for $C_3$ and $C_4$ crops will increase productivity in the form of grain yield, then likewise increase NUE as well as biological harvest. The strategies in which the N losses of $C_3$ and $C_4$ crops are reduced will boost the $C_3$ and $C_4$ crop productivity in future.

## 5. Conclusions

Reduced resource use efficiencies, such as NUE and RUE, in selected $C_3$ winter (wheat, oat, barley) and $C_4$ summer (maize, millet, sorghum) cereal crops could be augmented through splitting N fertilizer in irrigated arid conditions. The poor resource use efficiencies are due to lesser NUE in cereal crops and its possible losses by nitrification and runoff as well as leaching. Therefore, N application in three splits (at sowing time and first irrigation as well as second irrigation) to $C_3$ winter (wheat, oat, barley) and $C_4$ summer (maize, millet, sorghum) cereals may be considered as a substitute strategy to enhance resource use efficiencies by decreasing N losses in irrigated arid conditions.

**Author Contributions:** The authors contributed in the study in the following ways: S.H., M.A.A., A.A.K., M.A. and M.A.K. conceptualized the study; Q.A., M.I., M.I.S., M.N., U.F. and S.U.K. did field experimentation and related work; A.K., H.Y. and S.N. analyzed data using Software; K.J. did figure work; Z.F. and G.A. write first draft; S.A. did Supervision and overall Project Administration. All authors read the final draft before submission to journal.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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