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## Improving nitrogen-use and radiation-use efficiencies of C<sub>4</sub> summer cereals by split nitrogen applications under an irrigated arid environment

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**Abstract:** Increasing resource-use efficiency is of prime importance in sustainable agriculture. A field study was carried out to improve nitrogen-use efficiency (NUE) and radiation-use efficiency (RUE) of three C<sub>4</sub> summer cereals, i.e. maize, millet, and sorghum, under an irrigated arid environment. The results showed that among various cultivars of cereals, cultivars Pearl (maize), 18 BY (millet), and Jumbo (sorghum) produced the highest aboveground total dry matters and grain yields. The highest NUE and RUE were obtained by splitting the nitrogen dose 3 times, i.e. at sowing and at first and second irrigation. The NUE for maize, millet, and sorghum varied from 30.97 to 32.97, 21.34 to 23.32, and 17.39 to 20.22 kg kg<sup>-1</sup>, respectively. RUE ranged from 1.14 to 1.47, 0.85 to 1.08, and 0.91 to 1.13 g MJ<sup>-1</sup> for maize, millet, and sorghum crops, respectively. Maximum resource-use efficiency was achieved by 3 splits, while the minimum was obtained in the control group. It is inferred from this study that those varieties of C<sub>4</sub> summer cereals may be commercially grown that are more efficient in utilizing the available resources for harnessing greater NUE as well as RUE under an irrigated arid environment.

**Key words:** Maize, millet, nitrogen management, resource-use efficiency, sorghum

### 1. Introduction

Cereals constitute a greater proportion of diets by providing more than 70% caloric intake for people across the world. Among other cereals, maize (*Zea mays* L.), millet (*Pennisetum americanum* L.), and sorghum (*Sorghum bicolor* L.) are important C<sub>4</sub> summer cereals. Currently, the productivity level of cereals, and particularly C<sub>4</sub> summer cereals, in Pakistan is very low compared to other growing countries (Ahmad et al., 2012). The inherent low productivity is the result of poor utilization of natural resources (land and radiation) and inputs (water and fertilizers), resulting in less resource-use efficiency (Mahmood et al., 2013; Ahmad et al., 2015), and climate change (Rehman et al., 2015). Ironically, farmers growing summer cereal crops use age-old agronomic practices, rather than adopting the best agricultural practices to harness higher resource-use efficiency. Nitrogenous fertilizer is a major component of farm inputs to sustain the productivity of cereals, especially maize crops. The excess use of nitrogen (N)

fertilizer and even one-time dressing leads to losses in the form of nitrification, volatilization, and runoff, and even more so under adverse soil and climatic conditions (Ahmad et al., 2012). Nitrogen is the primary constituent for plant growth and development during vegetative and reproductive phases, thereby producing cumulative effects on nitrogen-use efficiency (NUE) and radiation-use efficiency (RUE) (Ahmad et al., 2012, 2015). It is of paramount importance to increase NUE by various management strategies to enhance RUE. Different N losses are the key causes for poor NUE in various agricultural systems. Thereby, N application in splits results in a substantial increase in NUE as an alternative for attaining higher RUE (Ahmad et al., 2015). This is due to decreases in N losses in various agroclimatic conditions, including irrigated arid environments. There is a growing concern that a major proportion of applied N is lost, resulting in lower NUE (Dawson et al., 2008). NUE is merely 29% in developing agricultural economies for raising cereal crops (Beatty et al., 2010).

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RUE is the amount of dry biomass (aboveground or total dry matter) produced per unit of intercepted solar radiation (Monteith, 1977). The RUE of assorted field crops including summer and winter cereals in the absence of biotic and abiotic stresses has been found to be moderately associated with crop-specific behavior (Hall et al., 1995) and has been researched in productivity modeling studies (Yang et al., 2004). However, RUE is mainly affected by various abiotic factors in general (Kemanian et al., 2004), water (Ahmad et al., 2008), nutrients and particularly N (Muurinen and Peltonen-Sainio, 2006), and environments (Lecoeur and Ney, 2003). The RUE for various crops also varies at different growth stages (Zahoor et al., 2010; Ahmad et al., 2015). In a recent study, Ahmad et al. (2012) reported that N split application as a top dressing along with a basal dose at sowing to  $C_3$  winter cereals in saline soils under irrigated arid environments may be adopted as an alternate strategy to enhance NUE and RUE by decreasing the losses of N fertilizer. Recent technological developments and their abilities to improve NUE and RUE encompass various crop managing strategies. However, there are some obstacles in attaining higher NUE and RUE within various crop species under the same ecoedaphic environments. This research was undertaken to demonstrate the impact of N split application regimes on NUE and RUE, and their associations, biomass accumulation, and grain yields, among various crop species under an irrigated arid environment.

## 2. Materials and methods

### 2.1. Site description

The field trials were conducted at the experimental farm of Bahauddin Zakariya University, Multan, Pakistan ( $30^{\circ}15'N$ ,  $71^{\circ}30'E$ ; 126.6 m a.s.l.). The area was under an arid environment and the soil texture class was silt clay loam. The soil was alluvial, calcareous, and alkaline in reaction. It was well drained and had no physical impediments for normal growth of the crops. The soil was medium in fertility status, having pH 8.02,  $EC_e$  2.3 dS/m,  $C_{org}$  0.76%,  $N_{tot}$  0.039%,  $P_{Olsen}$  5.1 mg/kg, and available  $K_{ext}$  110 mg/kg. Meteorological data during the crop season, i.e. daily minimum and maximum temperatures, daily solar radiation, and total precipitation during the study years of 2013 and 2014, are given in Figure 1.

### 2.2. Experimental design

The treatments included different varieties of three  $C_4$  summer cereal crops, i.e. maize (Sahiwal-2002, A; MMRI Yellow, B; Pearl, C), millet (YBS-93, A; YBS-89, B; 18 BY, C), and sorghum (Jumbo, A; YSS-98, B; YSS-9, C), and five nitrogen fertilizer splits: unfertilized, whole N at sowing, 1/2 N at sowing + 1/2 N at 1st irrigation, 1/3 N at sowing + 1/3 N at 1st irrigation + 1/3 N at 2nd irrigation, and 1/4 N at sowing + 1/4 N at 1st irrigation + 1/4 N at 2nd irrigation + 1/4 N at 3rd irrigation). Urea (46% N) was used as the

source of nitrogen fertilizer. The experimental plots were arranged in a randomized complete block design with a factorial arrangement having four replications.

### 2.3. Agronomic practices

The sowing date for all three experiments was 18 August for both years. The total N applied to the maize, millet, and sorghum crops was 227, 170, and 100 kg N ha<sup>-1</sup>, respectively. A total of four irrigations were applied, on 12 September, 28 September, 17 October, and 31 October, in both years. The N split application dates were 18 August, 12 September, 28 September, and 31 October. Final harvesting dates were 11 December, 6 December, and 14 December in both years for maize, millet and sorghum crops, respectively.

### 2.4. Data collection

Standard procedures were used to measure different growth- and development-related parameters. For leaf area index (LAI), a sample (10 g) of fresh leaves of the respective crop was taken and leaf area was noted using an area meter. Leaf area index was calculated according to Watson (1947):

$$LAI = \frac{\text{Leaf area}}{\text{Land area}}$$

RUE was calculated individually for each crop by the following equation:

$$RUE_{TDM} = \frac{TDM}{\sum Sa}$$

Here,  $\sum Sa$  is the cumulative photosynthetically active radiation (PAR), which was assumed to equal half (50%) of the daily total incident radiation, and TDM is the total dry matter (Szcicz, 1974). It was calculated by:

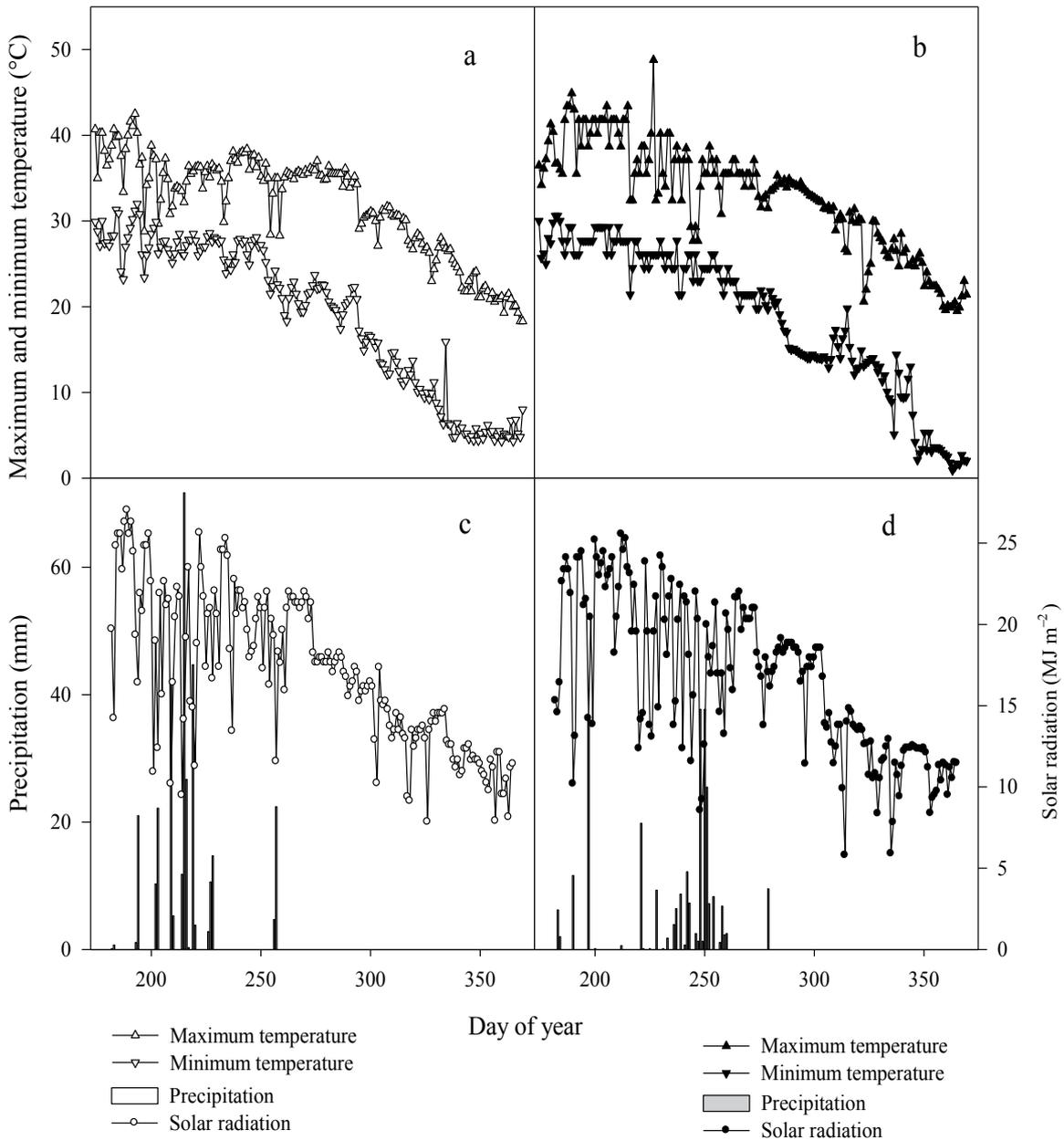
$$Sa = F_i \times S_i$$

Here,  $S_i$  is the incident PAR and  $F_i$  (fraction of intercepted radiation) was estimated from the respective crop leaf area indices using the following exponential equation (Monteith and Elston, 1983):

$$F_i = 1 - \exp(-k \times LAI)$$

Here,  $F_i$  is the fraction of intercepted radiation, 'k' is the extinction coefficient for total solar radiation, and LAI is leaf area index (Monteith, 1977). Values of 'k' for maize, sorghum, and millet were 0.65, 0.63, and 0.52, respectively (Monteith, 1969; Ong and Monteith, 1985; Anten et al., 1995). Multiplying these totals by appropriate estimates of  $F_i$  and  $S_i$  gave the amount of intercepted radiation (Sa) for the crops.

NUE was taken as the ratio of grain yield and amount of nitrogen applied and calculated according to Rahimizadeh et al. (2010):



**Figure 1.** Daily maximum and minimum air temperatures (a and b) and precipitation and solar radiation (c and d) during year 1 (unfilled symbols) and 2 (filled symbols) at Multan, Pakistan.

$$NUE = \frac{N_x (GY)}{N \text{ application rate}}$$

**2.5. Statistical analysis**

The data collected from these experiments were statistically analyzed by MSTATC computer software for analysis of variance (ANOVA). The treatment means were compared by using the least significant differences test (Steel et al., 1997).

**3. Results**

**3.1. Total dry matter**

The differential progression of TDM occurred through the vegetative stage to maturity among all varieties of the three summer cereal crops (Table). Averaged across N splits, TDM varied from 678 to 1733 g m<sup>-2</sup> among C<sub>4</sub> summer cereal crops (Figure 2). These crops had accumulated about half of the total TDM by anthesis. Maximum TDM was produced by maize, followed by sorghum and millet.

**Table.** The 1000-grain weight, grain yield, and total dry matter of C<sub>4</sub> summer cereals as affected by cultivars and N split application. Values in a column with different superscripts are significantly different.

	1000-grain weight (g)	Grain yield (g m <sup>-2</sup> )	Total dry matter (g m <sup>-2</sup> )	1000-grain weight (g)	Grain yield (g m <sup>-2</sup> )	Total dry matter (g m <sup>-2</sup> )	1000-grain weight (g)	Grain yield (g m <sup>-2</sup> )	Total dry matter (g m <sup>-2</sup> )
Cereals									
Cultivars	Maize			Sorghum			Millet		
A	332.18 b	731.00 a	1333.00 a	23.30 a	343.80 a	1137.80 a	12.75 a	233.20 a	1078.60 b
B	336.81 b	703.00 b	1294.40 b	19.14 c	295.60 b	1091.40 b	12.78 a	223.20 b	1047.20 c
C	356.60 a	748.40 c	1367.80 c	20.30 b	331.40 a	1116.60 a	11.80 b	213.40 c	1110.80 a
LSD 5 %	17.16	21.29	33.47	0.22	22.56	20.74	0.413	8.63	29.83
Nitrogen splits									
Control	340.42 c	429.33 c	703.66 c	19.35 d	234.66 c	737.00 b	12.27	168.33 c	716.33 c
Without split	348.24 c	776.00 ab	1438.33 ab	21.31 b	335.00 b	1189.33 a	12.26	228.00 b	1153.66 a
Two splits	361.44 b	827.33 a	1565.66 ab	21.48 b	357.00 ab	1232.00 a	12.43	249.00 a	1196.66 a
Three splits	383.97 a	882.66 a	1660.00 a	22.04 a	388.00 a	1284.00 a	12.54	266.00 a	1244.33 a
Four splits	275.24 d	722.00 b	1291.00 b	20.40 c	303.33 b	1134.00 a	12.73	205.00 b	1083.33 b
LSD 5%	9.50	147.05	333.12	0.48	51.63	192.65	0.534	33.29	183.29

Among maize cultivars, Pearl was more efficient (722 to 1733 g m<sup>-2</sup>) compared to Sahiwal-2002 (711 to 1640 g m<sup>-2</sup>) in producing TDM (Figure 2). The maize crops grown on three, two, and no N splits accumulated TDM in the descending order of 1660, 1565.66, and 1438.33 g m<sup>-2</sup>, respectively.

In the case of millet crops, maximum TDM (755 to 1283 g m<sup>-2</sup>) was produced by cultivar 18-BY compared to 711 to 1238 g m<sup>-2</sup> by YBS-93 under different N splits. Averaged across varieties, TDM was recorded in the descending order of 1244.33, 1196.66, and 1153.66 g m<sup>-2</sup> under three, two, and no splits of N fertilizer, respectively (Figure 2). In sorghum crops, averaged across N splits, cultivars Jumbo and YSS-9 produced TDM in the ranges of 777 to 1311 g m<sup>-2</sup> and 722 to 1276 g m<sup>-2</sup>, respectively. Averaged across varieties, the crops treated with three, two, and no N splits produced TDM in the order of 1284, 1232, and 1189.33 g m<sup>-2</sup>, respectively. The C<sub>4</sub> summer cereal crops under study reached the highest LAI peak level before the heading stage. However, values of the LAI peak differed substantially in response to varieties and N splits. Maize, millet, and sorghum attained peak LAI in the range of 3.5 to 5.2, 3.3 to 4.7, and 3.1 to 4.4, respectively (data not presented).

### 3.2. Grain yield

Data for grain yield (GY) of the three summer cereal crops differed significantly due to varieties and N splits (Table; Figure 3). The values of GY varied from 159 to 920 g m<sup>-2</sup>.

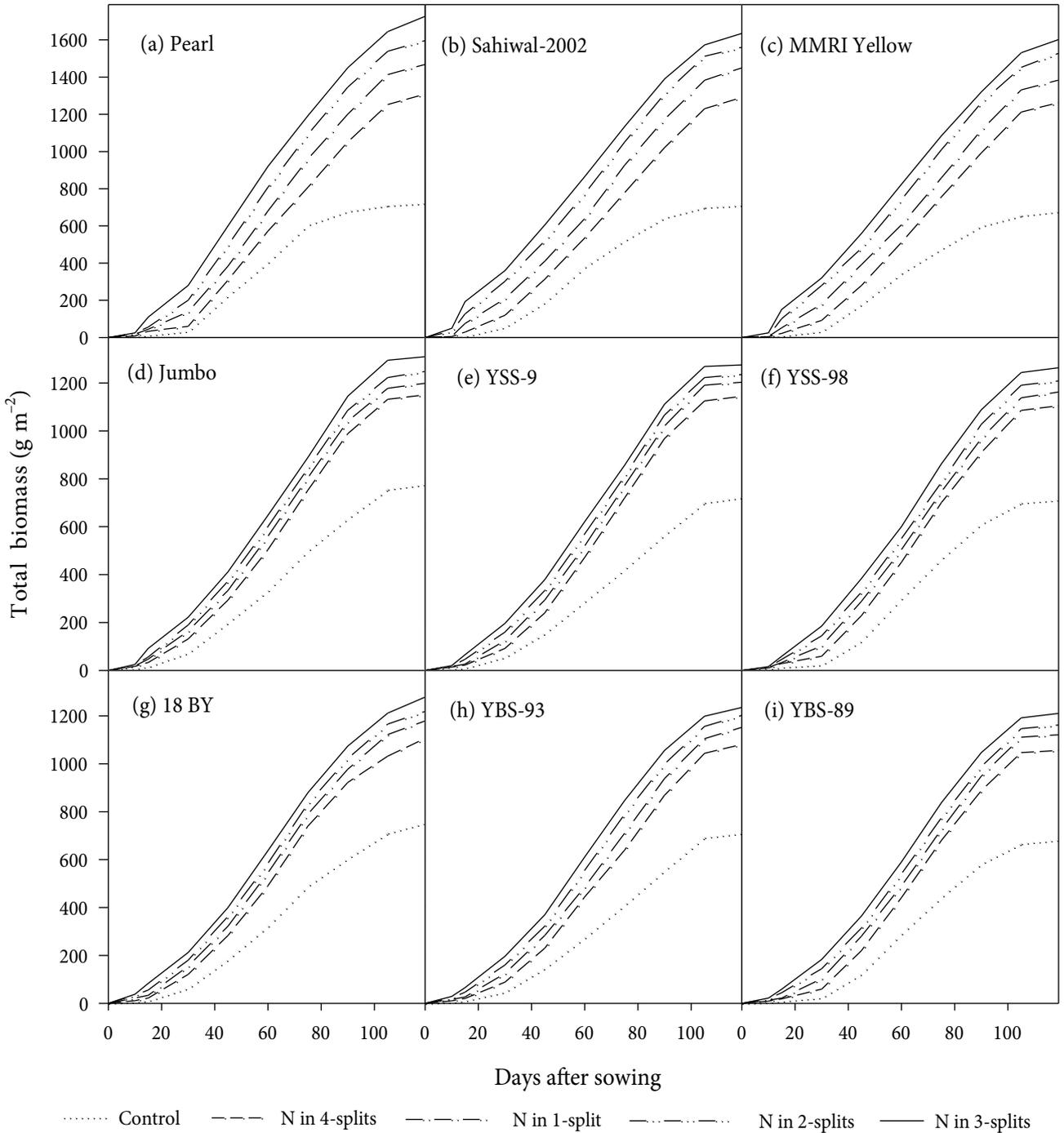
Maize yielded more than sorghum and millet. Averaged across N splits among maize cultivars, the maximum GY (433 to 920 g m<sup>-2</sup>) was produced by Pearl and 422 to 888 g m<sup>-2</sup> was produced by Sahiwal-2002. Averaged across varieties of maize treated with three, two, and no splits, N fertilizer produced GY in the descending order of 882.66, 827.33, and 776 g m<sup>-2</sup>, respectively (Figure 3). In the case of millet crops, averaged across N splits, cultivars 18-YB and YBS-93 produced GY in the ranges of 178 to 276 and 168 to 266 g m<sup>-2</sup>, respectively. Averaged across varieties, crops treated with three, two, and no splits resulted in production of GY in the order of 266, 249, and 228 g m<sup>-2</sup>, respectively. In sorghum crops, averaged across N splits, maximum (343.8 g m<sup>-2</sup>) GY was produced by Jumbo, followed (331.4 g m<sup>-2</sup>) by YSS-9 (Figure 3). Likewise, in other cereal crops, response to different N splits for GY was in the descending order of three, two, and no splits.

### 3.3. 1000-grain weight

Data for 1000-grain weights of the three C<sub>4</sub> summer cereal crops differed significantly for varieties and for N splits, except millet (Table). The values of 1000-grain weight for maize, millet, and sorghum varied from 11.80 to 383.97 g. Maize yielded more compared to sorghum and millet for 1000-grain weight.

### 3.4. Nitrogen use efficiency

Overall, NUE for maize, millet, and sorghum crops were within the range of 17.39 to 32.97 kg kg<sup>-1</sup>. The highest NUE of 38.88, 26.60, and 22.82 kg kg<sup>-1</sup> was achieved by



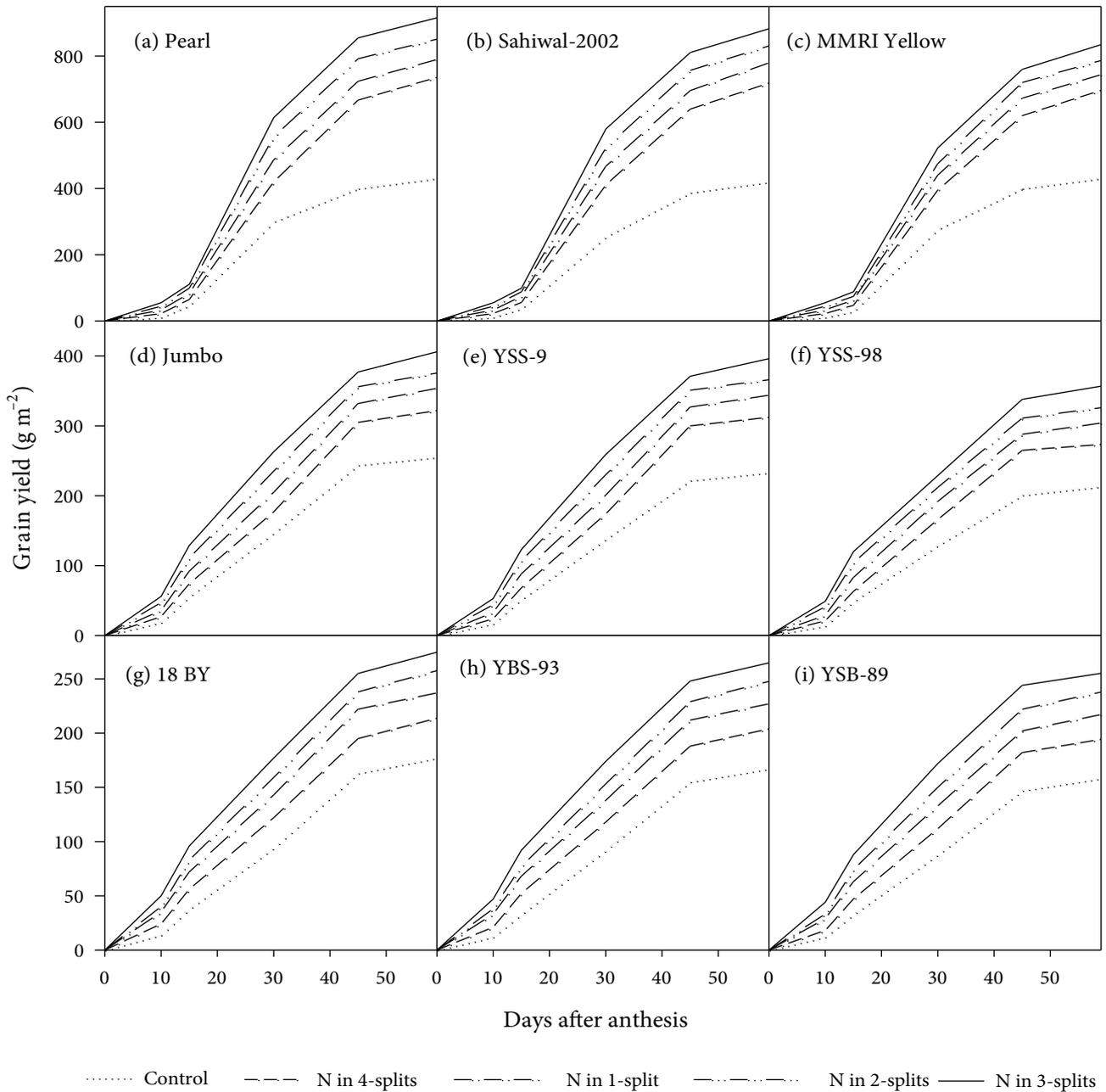
**Figure 2.** Total biomass production of maize (a, b, and c), sorghum (d, e, and f) and millet (g, h, and i) cultivars as affected by nitrogen split applications.

maize, millet, and sorghum crops grown on 3 splits of nitrogen fertilizer, whereas it was lowest in crops planted on soil treated with 4 splits of nitrogen fertilizer (Figure 4).

**3.5. Radiation use efficiency**

Data for RUE for maize, millet, and sorghum cultivars and diverse N splits differed significantly (Figure 5). Data for

TDM and cumulative intercepted PAR were well correlated in all N splits ( $R^2 > 0.88$ ). In the case of maize, millet, and sorghum crops, RUE ranged from 2.33 to 2.47  $g MJ^{-1}$ , 1.89 to 2.00  $g MJ^{-1}$ , and 1.96 to 2.04  $g MJ^{-1}$ , respectively. Overall, RUE for these three summer  $C_4$  cereals ranged from 1.89 to 2.47  $g MJ^{-1}$ , and for diverse N splits, it ranged from 1.26



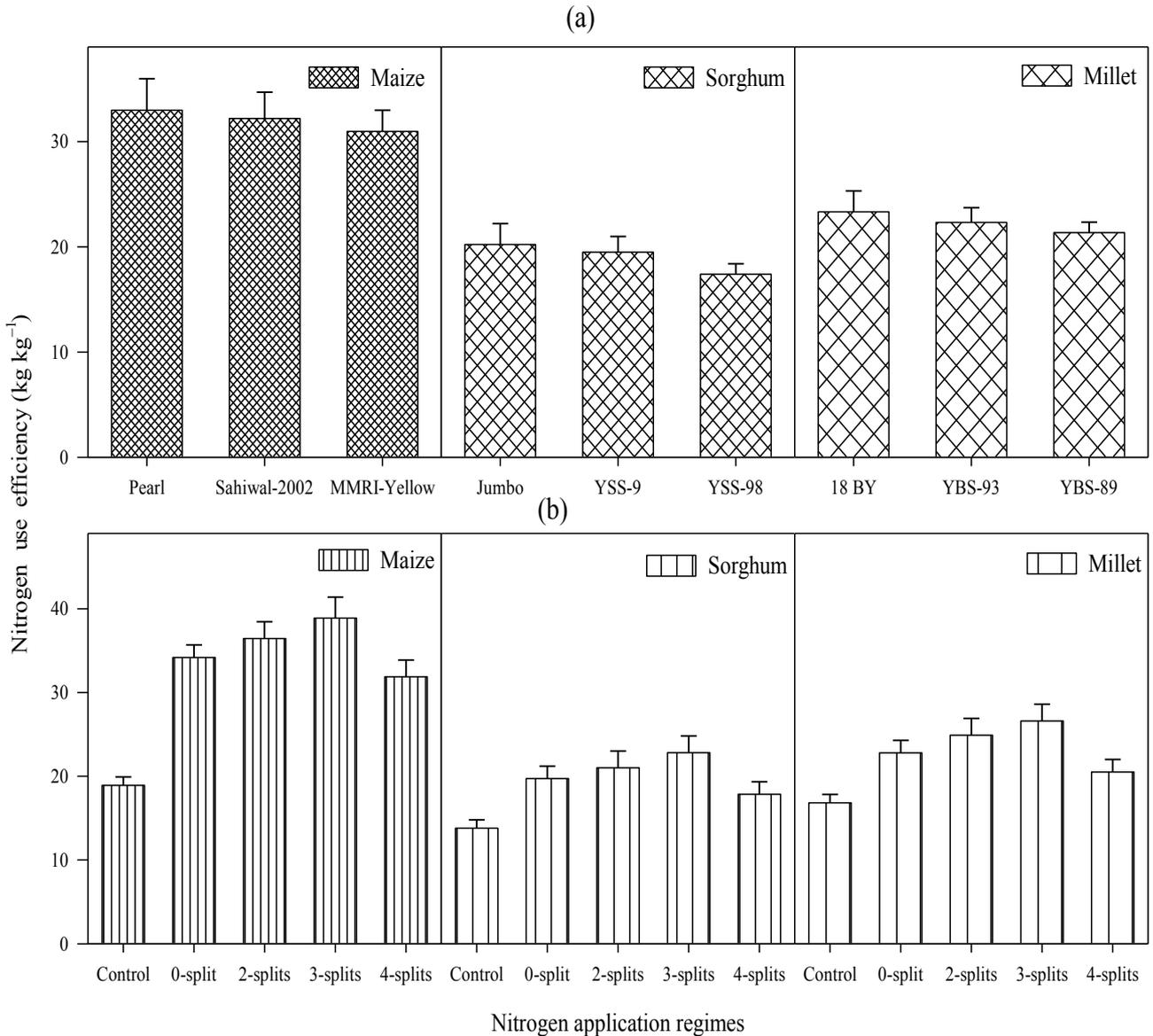
**Figure 3.** Grain yield of maize (a, b, and c), sorghum (d, e, and f) and millet (g, h, and i) cultivars as affected by nitrogen split applications.

to 2.99 g MJ<sup>-1</sup> (Figure 5). Among N splits, the highest RUE (2.99 g MJ<sup>-1</sup>) was recorded in the treatments where N was applied in three splits, while the lowest (1.26 g MJ<sup>-1</sup>) was in the control group (Figure 5).

**4. Discussion**

Cereals of the summer season with C<sub>4</sub> carbon metabolism were found with differences in accumulating TDM with variable N levels during the growing season. As a part of

TDM, grain yield and 1000-grain weight were also found to be different (Table). Variability in grain yield and TDM among different C<sub>4</sub> crops was according to plant species, reflecting a range in NUE among C<sub>4</sub> cereals (Reich et al., 1998). Leaf organic N contents are accumulated by CO<sub>2</sub> assimilation, i.e. NUE is critical in defining the efficiency of species by which they utilize N to achieve growth (Niu et al., 2003). Nitrogen applied in three splits remained well in all cereals. This shows that application of N in some

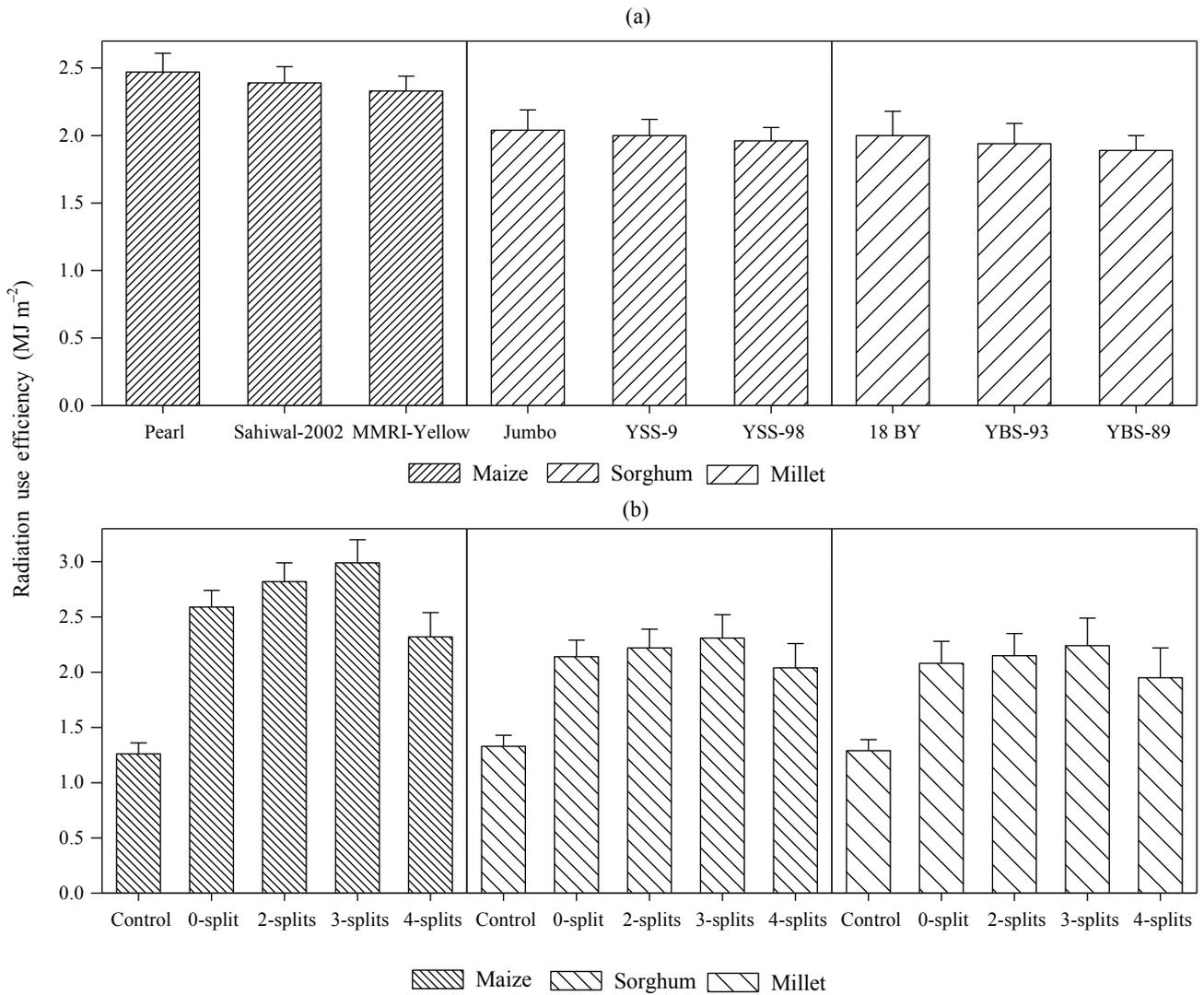


**Figure 4.** NUE of C<sub>4</sub> summer cereals as affected by cultivars (a) and nitrogen application regimes (b). Bars represent standard errors.

splits is better than application of all N at once or in many splits. The application of N all at once shows the tendency of N to decrease with time, which might be the result of an increase in plant biomass, or N losses due to volatilization or leaching (Sogbedji et al., 2000). Decreasing available soil N concentrations with increasing plant biomass reflects the increasing proportions of structural and storage materials containing N (Greenwood et al., 1990). Growth dilution effects with changes in N in plants necessitate the splitting of N applications. On the other hand, four splits cannot improve plant biomass and grain yield, reflecting a poor NUE. Nitrogen is strongly related to leaf photosynthesis and a better NUE shows good photosynthetic efficiency

(Foulkes et al., 2009; Ahmad et al., 2015). Variability in N dynamics and NUE has significant effects on photosynthetic efficiency, growth, and ultimately competition among plants, with subsequent impacts on dominance in different environmental conditions (Yuan et al., 2007).

Biomass accumulation of plants can be quantified by LAI, and more specifically by fixed carbon in photosynthesis and the part of that carbon changed to dry matter (Lindquist et al., 2005). This is actually a trait for the RUE of plants (Kiniry et al., 1999). Large differences are found among different cereals with respect to RUE (Sinclair and Muchow, 1999). In our experiment, RUE for maize, sorghum, and millet ranged between 0.85 and 1.08



**Figure 5.** RUE of C<sub>4</sub> summer cereals as affected by cultivars (a) and nitrogen application regimes (b). Bars represent standard errors.

g MJ<sup>-1</sup> and for N splits from 0.85 to 1.47 g MJ<sup>-1</sup>. The highest RUE (1.47 g MJ<sup>-1</sup>) in three splits shows a continuous N availability for plants. It is understood that with a better N supply, the RUE of summer cereals is improved (Muchow and Davis, 1988), which is in accordance with our results. Differences in RUE are the result of intercepted light or LAI (Lemcoff and Loomis, 1986). A range of LAI values for different summer C<sub>4</sub> cereals in our experiment was also recorded (data not shown). This inconsistency in LAI among different species can be a result of canopy architecture (Ahmad et al., 2012). Height of plants is of vital importance with respect to radiation distribution, its interception, and its utilization. Furthermore, the development of canopy in response to N fertilizer seems to play an important role in light interception (Muchow and Davis, 1988). In our experiment, leaf area was increased

with more N availability. As a result, RUE was found to be much better with constant N availability as compared to a discontinuity in N supply. Muchow and Davis (1988) also found a linear increase in TDM per unit of radiation intercepted in maize and sorghum. Such values of RUE with respect to applied N in maize and sorghum indicate that the RUE would be even better in maize than others on a total-biomass basis. Sorghum had more LAI as compared to maize. However, it seems insufficient for sorghum to accumulate leaf N for obtaining the level of maize. Adoption of N fertilizer splitting strategies for cereals will not only increase production, but will also improve NUE and biological yield. The reductions in loss of N fertilizer for growing cereals during the highest temperatures prevailing in the summer will aid in reducing the cost of production.

In conclusion, NUE and RUE in C<sub>4</sub> summer cereal crops, i.e. maize, millet, and sorghum, could be increased through application in splits under irrigated arid environments as compared to application once, which resulted in poor resource efficiencies. The reduced resource-use efficiencies are due to potential N losses through nitrification, runoff, and leaching. Therefore, nitrogen application in 3 splits, i.e. at sowing and at first and second irrigation, as top dressing to maize, millet, and sorghum (C<sub>4</sub> summer cereal) crops under irrigated arid environments may be considered as an alternate approach to augment NUE and RUE by minimizing N losses.

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