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Efficient rates of nitrogenous fertiliser for irrigated sweet sorghum cultivation during the post-rainy season in the semi-arid tropics

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ABSTRACT

Sorghum (*Sorghum bicolor* (L.) Moench) is a multipurpose crop with high tolerance to environmental stresses. To meet the increased demand for food and biofuel, current agricultural practices rely on the excessive use of inorganic nitrogen (N) fertiliser. However, excessive N fertiliser has resulted in negative environmental effects. In view of the varied N use efficiency (NUE) of plants under different environmental conditions, the aim of this study was to evaluate the efficient rates of N fertiliser in semi-arid tropics for sweet sorghum cultivation during post-rainy season by maximising NUE without compromising yield. Field experiments were conducted on two sweet sorghum cultivars with four different N fertilisation rates (0, 63, 90 and 150 kg N ha^{-1}) during the post-rainy season in India. Grain and stalk yields increased with N fertiliser, but significantly only up to 90 kg N ha^{-1}. The observed increases in grain yield were attributed by increases in kernel numbers. Corresponding with the differences in biomass, both relative growth rate (RGR) and crop growth rate (CGR) increased with N fertilisation rate up to 90 kg N ha^{-1}. Component analyses of RGR and CGR revealed that both net assimilation rate (NAR) and leaf area index (LAI) significantly contributed with increasing rates of N fertiliser applications. Furthermore, studies of NUE indices showed that agronomic N use efficiency (ANUE, indicating yield production per unit of fertiliser N) responded comparably up to 90 kg N ha^{-1}, and decreased significantly thereafter. Analysis of ANUE components showed that the decline in ANUE at 150 kg N ha^{-1} was due to a decrease in physiological N use efficiency (PNUE), indicating that the absorbed N was not utilised efficiently for biomass and yield production, but merely accumulated. These results together suggest that 90 kg N ha^{-1} is an efficient N fertilisation rate suggested among the tested treatments for sustainable sweet sorghum cultivation during the post-rainy season in the semi-arid tropics.

1. Introduction

Sorghum (*Sorghum bicolor* (L.) Moench), the fifth major food worldwide after maize, wheat, rice and barley (Paterson, 2008), is also staple food for half a billion people, particularly in the semi-arid tropics such as south Asia and sub-Saharan Africa (Mace et al., 2013). Sorghums, as a C_4 crop with high tolerance to environmental stresses, such as drought and heat, grow relatively well under adverse conditions (Teetor et al., 2011). For this reason, sorghum is cultivated mainly as an off-season crop (Filho et al., 2014) during the post-rainy season mainly in developing countries, including India, where day length is short and only residual moisture from the previous rainy season is used for cultivation. Sweet sorghum is a type of sorghum in which sucrose is accumulated in the stems in high concentrations, up to 15.5% (Regassa and Wortmann, 2014; Vinutha et al., 2014). These features, together with a relatively short growing time (3–5 months) as compared with sugar cane (7–12 months) (Almodares and Hadi, 2009) and higher energy use efficiency as compared with maize (Regassa and Wortmann, 2014) increase the attraction of sweet sorghum as an energy crop. Furthermore, sweet sorghum is a multipurpose crop with other uses such as grains for food and bagasse and leaves for fodder (Uchino et al., 2013).

With the rise in global population and the consequent food demand, there is an increasing need for agricultural production of biofuel as an alternative energy resource. To meet these increased

Abbreviations: ANRE, apparent nitrogen recovery efficiency; ANUE, agronomic nitrogen use efficiency; C, carbon; CGR, crop growth rate; DAS, days after sowing; DM, dry matter; EONR, economically optimum nitrogen rate; HI, harvest index; LAI, leaf area index; LAR, leaf area ratio; N, nitrogen; NAR, net assimilation rate; NHI, nitrogen harvest index; NUE, nitrogen use efficiency; PFP, partial factor productivity; PNUE, physiological nitrogen use efficiency; RGR, relative growth rate; Yp, the maximum yield potential.

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demands, current agricultural practices rely on the use of inorganic nitrogen (N) fertiliser (Kurai et al., 2011). N is a crucial nutrient for maximising the yield for farmers, particularly in developing countries where there is a large yield gap (Good and Beatty, 2011). Consequently, farmers tend to apply N fertilisers in excess for assuring yield (Sheriff, 2005). However, the use of large amounts of N fertiliser has resulted in negative environmental effects, such as pollution by nitrate leaching and nitrous oxide emission (Ramu et al., 2012) as well as ecological imbalance (Miller and Cramer, 2004).

One of the possible solutions to this situation is to enhance N use efficiency (NUE) of crops while maintaining the yield, and thus increasing the financial income of farmers. Among the multiple indices available for NUE assessment, agronomic NUE (ANUE) is the most informative in this case, as it describes grain yield per unit of N applied as fertiliser, indicating benefit-to-cost ratio (Cassman et al., 1996). As ANUE is a function of N uptake and N utilisation efficiency, component analysis of ANUE reveals whether uptake and/or utilisation of N is affected in a given environment. In maize, NUE was strongly affected by the utilisation of absorbed N under low N conditions, whereas N uptake efficiency was unaffected under high N conditions (Moll et al., 1982).

N availability is known to affect plant growth (Aerts and Chapin, 2000), and plants respond plastically to the surrounding environment both morphologically and physiologically (Useche and Shipley, 2010). Growth rate differences due to experimental treatments are often compared in the form of relative growth rate (RGR), which is a product of net assimilation rate (NAR) and leaf area ratio (LAR), responding physiologically and morphologically respectively. Changes in plant growth, particularly under limited N, affect plant biomass and grain yield. Crop growth rate (CGR) is an index of crop dry matter (DM) production, and can be divided into two components, NAR and leaf area index (LAI). LAI is another plant growth parameter known to be affected by N availability, and N uptake is reported to be directly proportional to LAI in many crops (Hirel et al., 2007). These component analyses of plant growth can be used to quantitatively interpret the effects of N fertilisation on plant development.

Muchow (1998) reported sorghum's variable response to N fertiliser depending on climatic, soil and genotypic conditions. We have previously reported optimum N fertiliser rates on sorghum during rainy season (Uchino et al., 2013). However, due to common practices of sorghum cultivation during post-rainy season in southern India, it is important to optimise N-fertilizer rates for the post-rainy season sorghum cultivation as well. In addition, no study has conducted NUE assessment in relation to plant growth analysis of sorghum in the semi-arid tropics to date. The aim of this study was to identify the efficient N fertiliser application rates for sustainable sorghum cultivation during the post-rainy seasons in the semi-arid tropics with focuses on assessments of growth analysis and multiple NUE indices in addition to yield in response to multiple N rates.

2. Materials and methods

2.1. Field experimental sites and conditions

The field experiment was conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) at Patancheru (17.53° N, 78.27° E, 545 m above sea level) near Hyderabad, India, during the post-rainy season (from late October to early March) of 2011–12 and 2012–13. The climate of experimental site is semi-arid with an average annual rainfall of 750–800 mm, approximately 80% of which is received between June and October (Ramu et al., 2012). Average air temperatures of the maximum and the minimum as well as amounts of precipitation for the first year and the second year of the experiments are illustrated in Fig. 1A and B, respectively. The same experimental plot was used throughout the experiment. Maize (*Zea mays* L.) was pre-cultivated each year for few months prior to the experiments without any fertiliser to deplete residual N, and the whole maize plants including roots were completely removed from the experimental site before the initiation of experiments each year. The main soil properties at various depths at the experimental sites before the initiation of experiments were measured according to Sahrawat and Wani (2013) and summarised in Table 1. In brief, available phosphate, potassium, sulphur, boron, and zinc were measured using sodium bicarbonate, ammonium acetate, calcium chloride, hot water and diethylenetriaminepentaacetic acid (DTPA) as extractants respectively. The soil of the experimental site is categorised to an Alfisol [Udic Rhodustalf by USDA classification (Soil Survey Staff, 1999) or Ferric Luvisols by FAO classification (FAO-UNESCO, 1977)]. The soil of the experimental site consists of sand [73.0% (0–18 cm) and 43.3% (18–71 cm), 2.0–0.2 mm in size], silt [6.0% (0–18 cm) and 5.6% (18–71 cm), 0.02–0.002 mm in size], and clay [(21.0% (0–18 cm) and 51.1% (18–71 cm), less than 0.002 mm in size] (El-Swaify et al., 1985).

2.2. Experimental design

The experiments were arranged as completely randomised block designs with three replications. Each plot had a size of 4.8 m × 9 m with a row spacing of 60 cm and plant-to-plant spacing of 20 cm, resulting in an average planting density of 8.3 plants m^{-2}. A promising sweet-sorghum hybrid in India, CSH 22SS, and a widely and commercially cultivated sweet-sorghum variety, ICSV

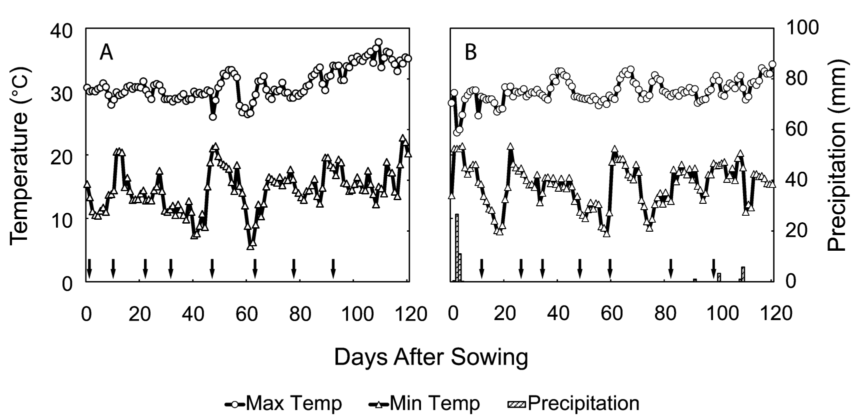

Fig. 1. Daily maximum and minimum air temperatures as well as precipitations were recorded in the experimental sites during the growing periods for the years 2010–2011 (A) and 2011–2012 (B). Black arrows indicate furrow irrigations provided every 2 weeks at an approximate depth of 90 mm.