Research Findings

Photo 1. Rice experiment plots at Annamalai University experiment farm, Chidambaram, India. Photo by P.K. Karthikeyan.

Influence of Potassium Application Management on Rice Production in Coastal Regions of South India

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Abstract

Rice (*Oryza sativa*) production is pivotal to the economy and food security in India; the country is second only to China in annual production. Nevertheless, and in spite of a significant increase during recent decades, yields lag behind potential rice productivity. Accurate and sophisticated mineral nutrition is a promising approach to enhance rice yield. The objectives of the present study are to examine and demonstrate the effects of potassium (K) dose, the number and timing of MOP (muriate of potash, KCl) application during the crop cycle, and the contribution of foliar SOP (sulphate of potash, K_2SO_4) at the reproductive stage on crop performance and productivity. The experiment took place at Chidambaram, Tamil Nadu, between June and September (Kuruvai), and included nine treatments: unfertilized control; standard nitrogen (N) and phosphorus (P) at 100 and 50 kg ha^{-1} of N and P_2O_5, respectively; standard NP + 25 kg K_2O ha^{-1} (soil-applied MOP, split into two applications) + two sprays of SOP at 1%, or 2%; standard NP + 37.5 kg K_2O ha^{-1} (soil-

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applied MOP, split into two applications) + two sprays of SOP at 1%, or 2%; standard NP + 50 kg K_2O ha^{-1} (soil-applied MOP, split into four applications); and, standard NP + 50 kg K_2O ha^{-1} (soil-applied MOP, split into three applications) + a single SOP spray at 1%, or 2%. Grain yields gradually increased from 2.37 Mg ha^{-1} under unfertilized control to 3.7 Mg ha^{-1} under the 50% K rate, and further to 5.5 Mg ha^{-1} under the highest K dose + SOP. Foliar SOP applications during early reproductive stages (panicle initiation and heading) had a significant effect on yield, with stepwise yield increments of 5-14%, on average. Based on these results, it is postulated that further optimization of NPK supply, including split N and K doses and foliar applications, adjusted as required during crop development, would lead to increased rice productivity.

Keywords: Foliar spray; harvest index; MOP; *Oryza sativa*; SOP; split application.

Introduction

Rice (*Oryza sativa*) is the staple food of more than 60% of world's population. Rice production is pivotal to Indian agriculture, as it occupies about 44 million ha (FAOSTAT, 2017) and accounts for about 40% of total food grain production in the country (India today web desk, 2018). Second only to China, and with 168.5 million tonnes, India contributed 21.8% of global rice production in 2017 (FAOSTAT, 2017). In years 2015-2016, with about 8 million tonnes a year, Tamil Nadu was the fourth rice producing state in India (India Today web desk, 2018).

Average rice yields in India increased significantly from about 1.5 Mg ha^{-1} in the 1960's to above 3.5 Mg ha^{-1} in the last decade (FAOSTAT, 2017). Undoubtedly, the achievement of raising the yield in recent decades can be largely associated with the higher potential of improved rice varieties (Khush, 1995; Yoshida and Nagato, 2011; Crowell *et al.*, 2016). Enhanced irrigation technologies and plant protection practices have also made a significant contribution to the rise in rice productivity (Krauss, 2001). Nevertheless, the most marked yield fluctuations, as well as well-recognized yield responses, emerge from nutrient application practices that must be carefully managed in order to realize the full yield potentials of rice (Kiuchi and Ishizaka, 1961; Bhowmick and Nayak, 2000; Dobermann and Fairhurst, 2000; Wang *et al.*, 2011).

Historically, the use of nitrogen (N) and phosphorus (P) fertilizers was disseminated successfully and became widespread among farmers (Kaushik *et al.*, 2012). However, increasing doses of N and P fertilizers, especially in the context of high-yielding cultivars, seem to have reached a saturation level, which indicates the occurrence of a new limiting factor - crop potassium (K) requirements (Mengel and Kirkby, 1987; Marschner, 1995; Dobermann *et al.*, 1996; Mae, 1997; Krauss, 2001; Wang *et al.*, 2011).

Potassium is vital to photosynthesis and in carbohydrate translocation and storage in the plant (Zörb *et al.*, 2014). Furthermore, K is deeply involved in the governance of plant water status, stomatal aperture, and osmotic regulation (Marschner, 1995; Cakmak, 2005; Zörb *et al.*, 2014). Soil type and properties play a major role in determining nutrient availability for crops. Among the three major nutrients, K availability is greatly affected by the soil characteristics, especially under marginal K status (Dobermann *et al.*, 1996; Zörb *et al.*, 2014). Rice is particularly responsive to K nutrition (De Datta and Mikkelsen, 1985; Dobermann *et al.*, 1998; Surendran, 2000; Liu and Yang, 2001; Yang *et al.*, 2004; Fageria, 2015; Xue *et al.*, 2016). However, the synchronization of K availability and the varying K requirements during crop development is essential to realizing yield potential (Dobermann *et al.*, 1998; Surendran, 2000; Liu *et al.*, 2001; Yang *et al.*, 2004; Mansour *et al.*, 2008; Xue *et al.*, 2016; Zain and Ismail, 2016).

MOP (muriate of potash, known also as potassium chloride, KCl) is the most common K fertilizer. It is highly soluble and is immediately accessible to plant roots in the soil soluble phase. Nevertheless, as such, K^+ ions might be rapidly fixated to soil particles in certain soil types but, furthermore, they might be leached away from the rhizosphere under excess water supply (Zörb *et al.*, 2014). SOP (sulphate of potash, K_2SO_4), providing Cl-free K with the advantage of sulfur (S) supplement, is a suitable alternative to MOP. Nevertheless, under soil-applied SOP, the fate of K^+ ions is similar to that under MOP (Ali *et al.*, 2005). Foliar nutrient applications, in this case SOP, were shown to partially replace soil application (Surendran, 2000; Ali *et al.*, 2007). Therefore, aiming to enhance the accuracy of K application and fit it to crop requirements during its course of development, the combination of split soil applications with supplement foliar sprays seems promising.

The objectives of the present study are to examine and demonstrate the effects of K dose, the number and timing of MOP application during the crop cycle, and the contribution of foliar SOP at the reproductive stage on crop performance and productivity.

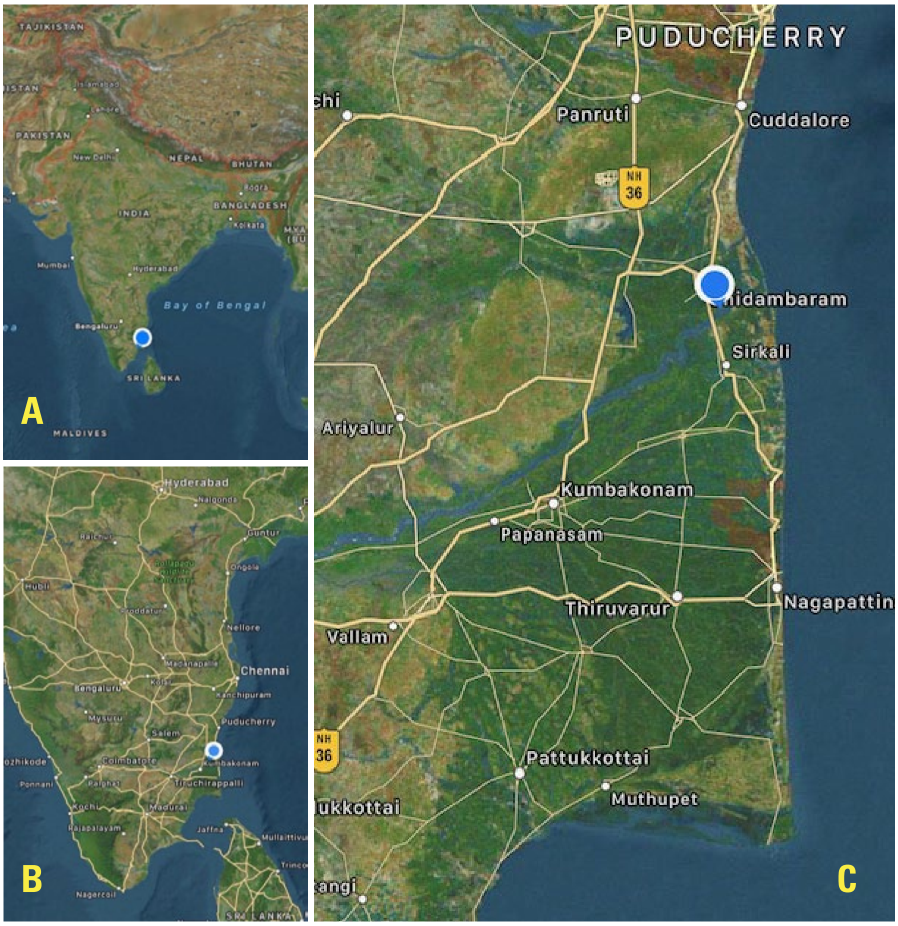
Materials and methods

A field experiment was carried out on field A-8 of the wetland block at Annamalai University experimental farm, Chidambaram. The experimental farm is geographically located at 11°24'N latitude and 79°41'E longitude, 6 km away from Bay of Bengal, at an altitude of 5.79 m above mean sea level (Map 1).

The soil of the experimental field was deep, moderately drained, clay in texture with pH 8.3. The soil was low in available N (239 kg ha^{-1}), medium in available P (15.0 kg ha^{-1}), medium in available K (240 kg ha^{-1}), and high in available S (15.6 mg kg^{-1}). Soil samples were taken and analyzed for various physico-chemical properties before planting (Table 1).

The field experiment was carried out during 110 days of the Kuruvai season (June-September), when precipitation rates increase but before the heavy monsoon rains begin, and while temperatures gradually decrease from the summer peak (Fig. 1).

The locally common short duration rice variety ADT-43 was planted at a spacing of 12.5 x 15 cm. The recommended fertilizer dose of 100, 50, and 50 kg ha^{-1} of N, P_2O_5, and K_2O, respectively, is referred to as the standard (100%). Half of the N dose was applied basally in the form of urea (46% N) and the remaining 50% was split into two equal amounts and top-dressed at tillering and panicle initiation stages. Phosphorus was applied basally in the form of superphosphate (SSP, 16% P_2O_5). Potassium was applied according to the designated treatments (Table 2) in the form of MOP to the soil, and SOP as foliar spray. The experiment included nine treatments, with the first two serving as controls: an absolute control (no fertilizer), and standard NP dose with no K fertilizer. In the other seven treatments, K dose was gradually increased from 50 to 100% and included different combinations of split K dose and foliar applications at different crop development stages. A detailed description of treatments is provided in Table 2. The experiment was laid out in a randomized block design (RBD) with three replications. Individual plot size was 5 x 8 m.



Map. 1. The experiment site at Chidambaram, Tamil Nadu, India (A), on the south-east coast (B), near the Kollidam river delta (C). *Source:* Google Earth.

Table 1. Soil properties at the experiment field, determined before planting.

Soil property	Value
Clay (%)	43.4
Silt (%)	15.8
Coarse sand (%)	15.3
Fine sand (%)	25.1
Soil textural class	Clayish
pH soil reaction	8.3
EC (dSm^{-1})	0.56
Organic carbon (g kg^{-1})	0.63
Available N ($KMnO_4$-N; kg ha^{-1})	239 (low)
Available P (Olsen's; kg ha^{-1})	15.0 (medium)
Available K (NH_4O-Ac; kg ha^{-1})	180 (medium)

Five representative samples from each plot were tagged randomly for the determination of crop developmental stages - tillering, panicle initiation, bloom, and harvest. The experimental crop was harvested plot-wise by cutting the stem closer to ground level. Grains were separated by hand threshing, winnowed, cleaned, and sun dried to bring the moisture content to the standard level (14%). The straw was sun dried. The grain and straw yields were determined separately and the harvest index calculated as the ratio between grain yield and the total aboveground dry biomass.

Results

Dry aboveground biomass

With the limits of measuring root biomass, the dry aboveground biomass is a principal indicator of environmental effects on primary production - photosynthesis and growth. The increasing contribution of fertilizer applications, as treatments climb from null through NP, and further to NPK with gradually intensified modes of K application, was obvious (Fig. 2). Almost each step of introducing more nutrients or of increased nutrient availability brought about a significant rise in dry matter (DM)

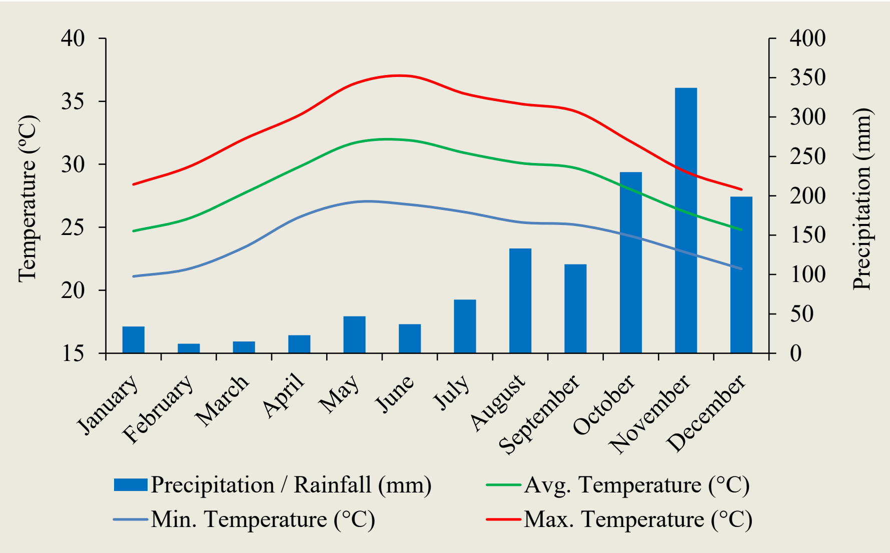


Fig. 1. Mean monthly temperatures and precipitation at Chidambaram, Tamil Nadu, India. *Source:* https://en.climate-data.org/asia/india/tamil-nadu/chidambaram-52335/#climate-graph.

production. The lowest DM yield, 6.3 Mg ha^{-1}, was obtained at the absolute control treatment, where no nutrients had been applied. Supplying NP alone increased the DM production by 25%, and the addition of a half dose K contributed about 17-25% more DM yield. Increasing K application to 75%, and further to the full-recommended dose of 50 kg K_2O ha^{-1} added about 15% DM rise each, resulting in 11.3 Mg ha^{-1}, which was about 80% more than at the absolute control. The role of the foliar SOP application during the later stages of crop development was remarkable. At the low and medium K rates (50 and 75%), increasing SOP concentration from 1 to 2% gave rise to significant growth of 7 and 10%, respectively, in the DM yield (Fig. 2). Furthermore, at the highest K rate (standard, 100%), a single foliar SOP application at 1% increased DM production by 11.4% above the standard, 4-split soil-applied MOP, while 2% SOP resulted in no further difference (Fig. 2). Finally, the standard NPK treatment, with 3-split soil-applied MOP, and a single foliar application at 1% SOP obtained the highest DM yield - 12 Mg ha^{-1}, 100% more than at the absolute control (Fig. 2).

Grain and straw yields

The pattern of the effects of fertilizer treatments on the grain yield was similar to that shown for the DM production but significantly greater (Fig. 3A). While the control grain yield was the lowest, 2.37 Mg ha^{-1}, the highest grain yield was obtained by the NP+K_{100}+1%SOP treatment, 5.45 Mg ha^{-1}, which was 130% greater. Also, in the case of grain yield, each step towards a higher rate or improved nutrient availability resulted in a significant yield increase; however, the rate of this increase was, on average, about 16.6% per each step, much higher than the corresponding rate of DM increase, 12.5%. Similar to DM production, the foliar SOP applications during the late stages of crop development had a significant effect on grain yield, as indicated by the upsurge of 11-13% whenever SOP concentration was raised from 1 to 2%. Another indication can be found in the increase from 75 to 100% K, where grain yield increase was substantially pronounced as a result of 1% SOP application, rather than following a 4-split soil-applied MOP (Fig. 3A). On the other hand, increased SOP concentration to 2% made no further contribution to the grain yield.

In contrast to grain yield, straw production response to the fertilizer treatments was significantly smaller (Fig. 3B). It increased from 3.64 Mg ha^{-1} at the control, to 4.7 Mg ha^{-1} (29%) in response to NP application, and rose further by an additional 15% when applied with the half K dose. However, the straw biomass remained quite constant at 5.4-5.8 Mg ha^{-1} under increasing K supply. The next significant rise in straw yield was obtained under the full K dose, with added foliar application of 1% SOP (Fig. 3B).

The response of the harvest index (HI) to the fertilizer treatments was particularly interesting, as it indicates the influence of the various nutrients and the timing or mode of application on the dry biomass allocation between vegetative

Table 2. A detailed description of the fertilizer treatments. The N dose, 100 kg ha^{-1}, was split to basal (50%) and two equal applications at tillering and panicle initiation. P_2O_5 was applied basally. The standard K dose (100%) was 50 kg K_2O ha^{-1}. MOP dose was evenly split among applications.

Treatment code	NP (%)	K (%)	Timing of MOP applications				Concentration and timing of SOP foliar applications	
			Basal	Tillering	Panicle initiation	Heading	Panicle initiation	Heading
Control	-	-	-	-	-	-	-	-
NP+K_0	100	0	-	-	-	-	-	-
NP+K50%+1%SOP	100	50	+	+	-	-	1%	1%
NP+K50%+2%SOP	100	50	+	+	-	-	2%	2%
NP+K75%+1%SOP	100	75	+	+	-	-	1%	1%
NP+K75%+2%SOP	100	75	+	+	-	-	2%	2%
NP+K100	100	100	+	+	+	+	-	-
NP+K100%+1%SOP	100	100	+	+	+	-	-	1%
NP+K100%+2%SOP	100	100	+	+	+	-	-	2%

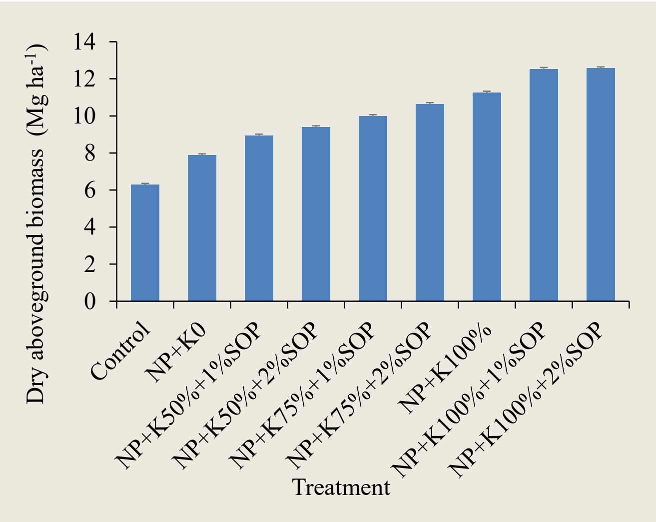


Fig. 2. Effects of fertilizer treatments on the dry aboveground biomass of rice grown at Chidambaram, Tamil Nadu, India. Detailed description of treatments is given in Table 2. Bars indicate $LSD_{0.05}$.

and reproductive growth (Fig. 3C). Nitrogen and P application slightly decreased HI from 0.377 to 0.364, at the control and NP treatments, respectively. Potassium application at half dose significantly shifted dry matter to the reproductive organs only when supported by foliar applications of 2% SOP. HI response to increasing K rates continued up to the K75% +2% SOP treatment, where it reached 0.44. However, HI did not respond to any further increase in K rate or availability (Fig. 3C).

Figure 4 illustrates the influence of the different fertilizer treatments on the development of the reproductive organs and, consequently, on the yield parameters. Unequivocally, the fertilizers had a direct effect on the number of grains per panicle (Fig. 4A), which grew gradually with each step towards a higher nutrient availability. The most significant effect, a 27% increase, was observed from unfertilized control to the NP treatment, whereas the relative effect of the increasing K rate or availability decreased each step but remained positive. The only case where grain number did not respond was when the SOP concentration was increased from 1 to 2% at the full dose K rate treatment (Fig. 4A).

While panicle length responded in a pattern similar to that of the number of grains (Fig. 4B), the influence of the fertilizer treatments on grain weight was much less consistent (Fig. 4C). The latter increased significantly in response to NP application, but the soil-supplemented K at its lower rate, including foliar SOP, did have any effect on grain weight. Nevertheless, raising the K rate to 75% of the standard dose, including foliar SOP applications, increased grain weight by about 7%, from 13.8 to 14.8 g $1{,}000^{-1}$. Interestingly, when the full standard K dose was soil-applied in the form of MOP, grain weight significantly

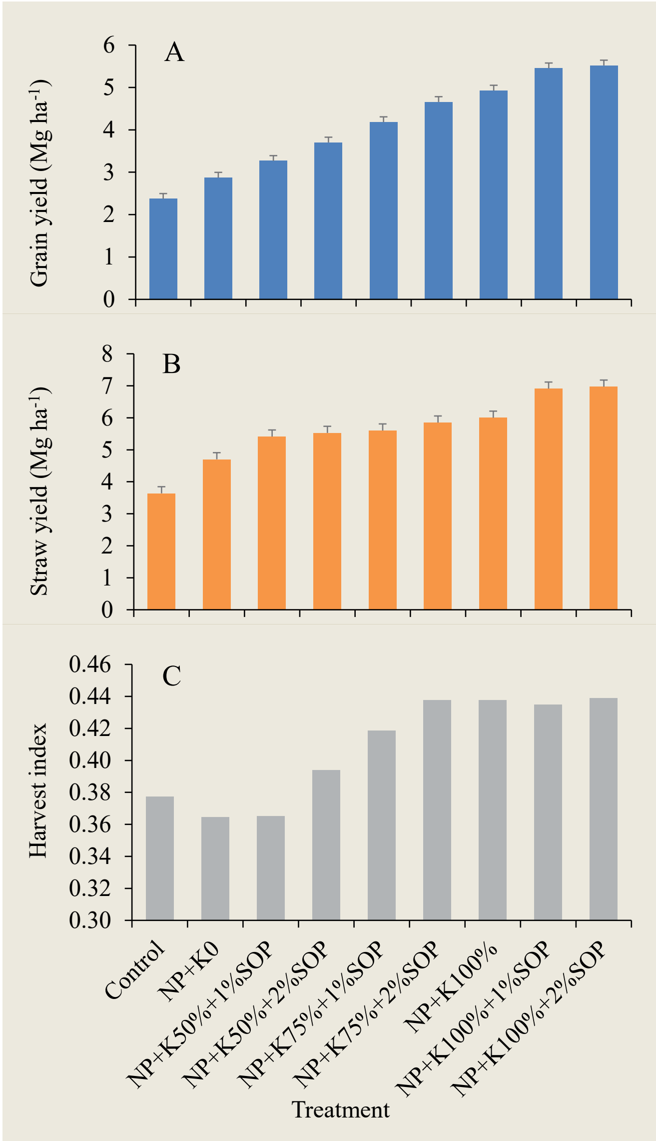


Fig. 3. Effects of fertilizer treatments on the grain (A) and the straw yields (B), and on the harvest index (C) of rice grown at Chidambaram, Tamil Nadu, India. Detailed description of treatments is given in Table 2. Bars indicate $LSD_{0.05}$.

declined by 5%, compared to the former reduced K level. However, when the standard K dose was applied in combination with a single foliar SOP spray (1% or 2%), grain weight surged by 5%, from 14.9 to 15.7 g $1{,}000^{-1}$.

Discussion

Rice production is pivotal to human nutrition as well as to the economy of India in general, and particularly Tamil Nadu. Therefore, effective means to enhance rice crop performance, yield, and quality are extensively sought. The present study successfully demonstrates how basic principles of crop nutrition, when wisely practiced, can become a useful tool to maximize rice yields.

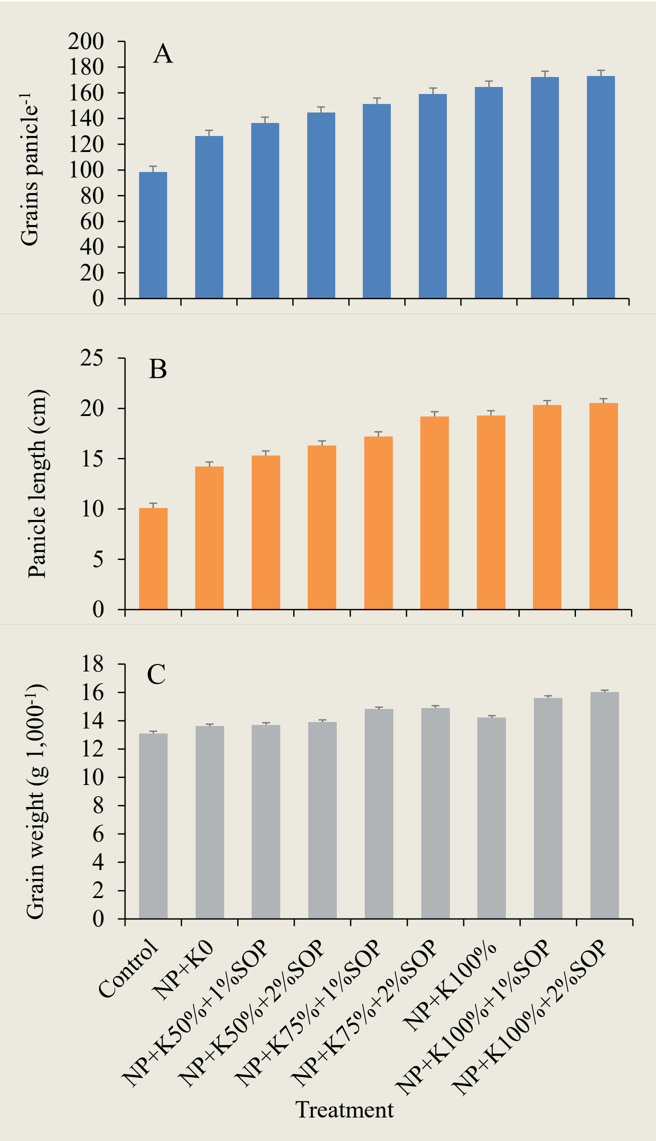


Fig. 4. Effects of fertilizer treatments on the number of grains per panicle (A), panicle length (B), and on grain weight (C) of rice grown at Chidambaram, Tamil Nadu, India. Detailed description of treatments is given in Table 2. Bars indicate $LSD_{0.05}$.

As expected, when no fertilizers are applied, rice biomass and grain yields are extremely low (Figs. 2 and 3). As most farmers already know and practice, applying N and P significantly increase yields; in the present study, this fundamental nutrition practice gave rise to 25, 20, and 30% more biomass, grains, and straw, respectively (Fig. 5). When applied in the form of urea, which is a relatively short-term fertilizer under warm and humid conditions (Rawluk *et al.*, 2001), N dose should be split during the crop cycle and applied at the most relevant stages of development (Mae, 1997; Krauss, 2001). Phosphate fertilizers are usually much more stable, and hence a single basal application would be appropriate (Dobermann *et al.*, 1998).

Potassium, in spite of its fundamental roles in plant physiology and its tremendous potential to enhance the performance and yield of numerous crop species (Marschner, 1995; Cakmak, 2005; Zörb *et al.*, 2014), including rice (De Datta and Mikkelsen, 1985; Fageria, 2015; Zain and Ismail, 2016), is still ignored by most farmers (Kaushik *et al.*, 2012). Applying half of the recommended K dose, with two additional foliar sprays of SOP (1%), was sufficient to raise rice dry biomass, grains, and straw by 14-15% (Fig. 5). These results suggest that at basic levels, K is required, in concert with N and P, for the buildup of plant vegetative biomass thus determining its potential productivity. The yield obtained by this fertilization practice (recommended N and P doses + 50%K+1%SOP) is close to the average rice yield level in India in 2017, 3.85 Mg ha^{-1} (FAOSTAT, 2017), providing some indication with regards to rice nutrient status in the country.

Nonetheless, stepwise increases of K dose or K availability clearly demonstrated the significance of K role in the reproductive phase and the consequent determination of the grain yield. Thus, on a similar background of 50% K dose but with doubled SOP concentration at the two foliar applications, grain yield increased further by 13.3%, with much lower contribution to the straw yield (Fig. 5). Similar patterns of relative increase in grain and straw yields were observed when the soil-applied K dose was raised to 75% with 1% SOP sprays, and again, when SOP concentration was doubled. The shift from the vegetative to the reproductive phase prior to panicle initiation brings about significant changes in plant nutrition. Before that shift, soil-applied nutrients dominate plant mineral uptake and balance, with root function playing a key role in the process. Sufficient K supply positively affects root development and subsequently enhances shoot growth and overall plant biomass (Cai *et al.*, 2012; Zhao *et al.*, 2016). After the shift, all plant resources are conveyed to construct and secure the next generation - the grains. Stored carbohydrates and nutrients are remobilized and translocated to the reproductive organs (Araki, 2001). Potassium has key functions in remobilizing carbohydrates (Yang *et al.*, 2004; Xue *et al.*, 2016; Zain *et al.*, 2016). While root growth and mineral uptake decline during the reproductive phase (Poethig, 2010), the internal K status of the plant might often be a serious limiting factor. Foliar applications at this stage appear to be very useful in such cases, as shown clearly in the present study. Under lower levels of soil-K availability, foliar SOP applications brought about significant increases in the aboveground dry biomass (Fig. 2), especially through a substantial rise in the grain yield, which is strongly reflected in the dramatic change in the harvest index (Fig. 3). It appears that the main effect of SOP sprays at panicle initiation and heading was at a very early and sensitive stage - grain set - as they influenced grain number and panicle length, rather than grain weight (Fig. 4).

Another example of the significance of foliar K applications at late developmental stages was found in crop response when the full K dose had been administered through soil MOP applications. Under no SOP application (NP+K100%), crop performance improved very slightly compared to the former treatment (NP+K75%+2%SOP), while grain weight even declined (Fig. 4C). The upsurge in most parameters in response to a single foliar SOP application at heading (Fig. 5) suggests that the additional K absorbed through the canopy promoted supplementary resource recruiting from the roots to the shoots. Alternatively, it could have expanded the carbon assimilation period. Altogether, the surplus K in the leaves generated significant growth, which was allocated equally to grains and straw.

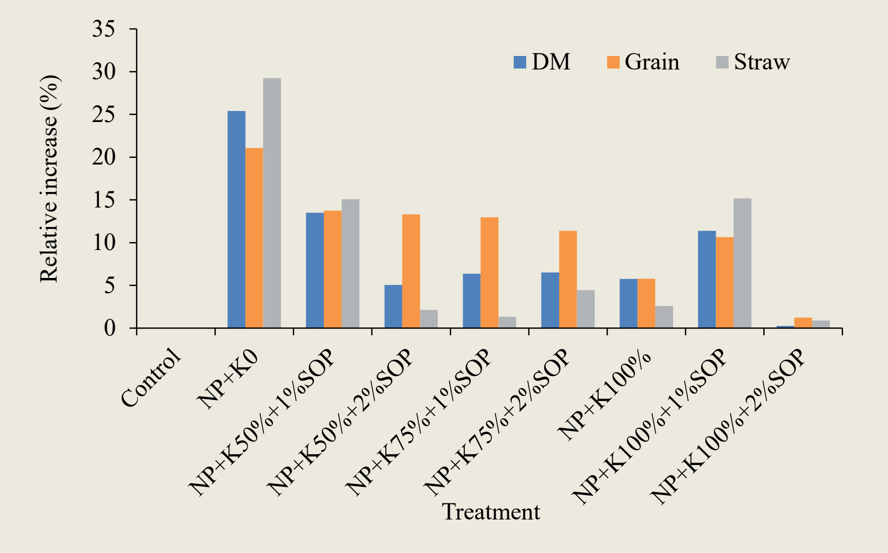


Fig. 5. The response of DM, grain and straw yields to stepwise rises in nutrients dose and availability in rice grown at Chidambaram, Tamil Nadu, India. Values represent the relative increase at each step.

Photo 2. +K and -K in early stages of growth in rice. Photo by P.K. Karthikeyan.

Testing K rates higher than the recommended dose (50 kg K_2O ha^{-1}) was beyond the frame of the present study. It may be assumed, however, that attempts to further increase rice yields under this set of conditions by additional K supply would encounter some limiting factors. Increasing the N and P doses might open new horizons for higher K rates in an attempt to raise rice yields even more. The yield levels obtained in the present study at the highest K rates, about 5.5 Mg ha^{-1} (Fig. 3A), are 50% higher than the current average rice yield in India. However, as indicated by the current average rice yield in USA (about 7.9 Mg ha^{-1}), there is still substantial potential to improve. A solid way to enhance rice crop performance further would be to optimize N, P, and K doses and application practices, including accurate timing and quantities of K applications during the course of crop development.

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