

REGULAR ARTICLE

Effect of nitrogen fertilizer on yield and nitrogen use efficiency of four aromatic rice varieties

Koffi Djaman*, Boubie V Bado, Valere C Mel

Africa Rice Center (AfricaRice) -Regional Sahel Station, Senegal, B.P. 96 St Louis, Senegal

ABSTRACT

The objective of this study was to optimize nitrogen fertilizer for higher yield and nitrogen use efficiency of four aromatic rice varieties. Field experiments were conducted at Ndiaye and Fanaye (Senegal) during the hot and dry season 2012 and the wet season 2012 to evaluate the effect of nitrogen on rice yield and nitrogen use efficiency under phosphorus and potassium omission management. Five rates of nitrogen (0, 60, 90, 120 and 150 kg/ha) were associated with P (26 kg P/ha); or P-K (26 kg P/ha and 50 kg K/ha). Four aromatic rice varieties Pusa Basmati, Sahel 329, Sahel 177 and Sahel 328 and a non-aromatic variety Sahel 108 were evaluated. Results showed that across genotypes, rice yield varied from 3.3 to 8.6 Mg/ha under N-P fertilizer and from 3.5 to 8.8 Mg/ha under N-P-K fertilizer at Ndiaye. At Fanaye, rice yield varied from 3.7 to 8.6 Mg/ha under N-P fertilizer and from 3 to 10.3 Mg/ha under N-P-K fertilizer. The highest grain yield was obtained by Sahel 177 among the aromatic rice varieties. The optimum nitrogen dose varied with rice genotype and location. The PFPN and the ANUE were influenced by genotype and varied from 161 to 28 kg grain/kg N and from 105.9 to 0.9 kg grain/kg N, respectively. The highest PFPN was obtained by Sahel 108 followed by Sahel 177. K addition to N-P significantly increased ANUE from 6.4 to 20.78 kg grain/kg N. The aromatic rice variety Sahel 177 is the performing alternative to the non-aromatic rice Sahel 108 in Senegal.

Keywords: Aromatic rice; Nitrogen use efficiency; Production function; Yield

INTRODUCTION

Fertilization and irrigation are the two most important practices in crop and resource management and nitrogen fertilizer is usually applied at greater rates than any other plant nutrient, making it the most expensive fertilizer input in rice production (Fageria et al., 1997). Imbalanced nitrogen fertilizer applied rate in soils is the most important variable that limits the quality and yields in rice (Wang et al., 2008). Nitrogen is the main nutrient that determines rice yield, due to its role in the photosynthesis, biomass accumulation and, spikelets formation (Hasegawa et al., 1994; Yoshida et al., 2006). Nitrogen influences the number of productive tillers per plant, yield and yield components as reported by Jashim et al. (1984). Significant improvement in crop yields is attributed to the increase in fertilizer use, especially nitrogen fertilizer (Cassman et al., 2003). At farmers level, the rate of applied N fertilizer is usually greater than the recommendation for maximum crop growth and maximum yields (Fan et al., 2012). However, excessive N input could cause groundwater pollution by nitrates, increase the rice production cost, and reduce paddy yield and contribute

to global warming (Peng et al., 2009; Pen et al., 2010; Guo et al., 2010; Fan et al., 2012). Nitrogen fertilizer recommendation can be based on addressing soil residual nitrogen or yield target however, real time N management and site specific nitrogen management are revealed more profitable, taking into account the temporal and spatial variability in soil properties with the least environmental negative effects (Ferguson et al., 2002; Herell et al., 2011; Djaman et al., 2013). In the mid-southern United States, nitrogen fertilizer recommendations for rice production are state specific, variety specific, and depend on soil type and crop management practices based on long-term and multi-location field experiments (Guindo et al., 1994; Snyder and Slaton, 2002; Dunn and Stevens, 2006; Norman et al., 1997, 2000; Harrell et al., 2011).

In Senegal, national nitrogen rate recommended to maximize rice productivity is 120 kg N/ha regardless rice genotype and yield potential, soil residual nitrogen and yield target (SAED, 2011). Over fertilization of N causes low N use efficiency (NUE). Agronomic nitrogen use efficiency (ANUE) (yield increase due to N fertilizer application)

*Corresponding author:

Koffi Djaman, Africa Rice Center (AfricaRice) -Regional Sahel Station, Senegal, B.P. 96 St Louis, Senegal. E-mail: k.djaman@cgiar.org, Tel. 002217800165660

Received: 14 May 2015;

Revised: 02 January 2016;

Accepted: 05 January 2016;

Published Online: 05 January 2016

was reported to be less than 10 kg kg⁻¹ N (Peng et al., 2010; Fan et al., 2012). Previous study in the Senegal River Valley showed that yield of rice variety Sahel 108 increased significantly with applied rates of N with lower internal N efficiency at Ndiaye than at Fanaye (de Vries et al., 2010). The same authors indicated that other factors than N might have constrained rice yields at Ndiaye. Mahajan et al. (2010) reported that the optimum nitrogen-fertilizer rate was 40 kg N/ha. However, they indicated that the optimum N rate for rice cultivar 'Punjab Mehak 1' was 60 kg N/ha. Peng et al. (2004) reported that maximum yield was obtained under 60–120 kg N/ha, while farmers were applying 180–240 kg N/ha in China. Susamma et al. (2005) evaluated the performance of 12 aromatic rice varieties/cultivars and showed that 'Pusa Basmati1' obtained the highest paddy yield of 2.8 Mg/ha which was statistically similar to that of 'Jeerakasala' (2.7 Mg/ha and IET12606 (2.6 Mg/ha), implying the suitability of these three varieties for cultivation in Ambalavayal, Wayanad district. The Basmati varieties have yield potential of 4.5 - 6 Mg/ha but on farm yields range from 2.0 to 2.8 Mg/ha (Ahmad et al., 2005; Shivay et al., 2010). Aromatic rice consumption has increased in recent years and the possibilities for export offer an opportunity to increase the production (Das and Baqui, 2000).

Whenever the yield of aromatic rice varieties is low (Gangaiah and Prasad, 1999), its higher price and low cost of production generated higher marginal profit than other varieties (Farook et al., 1999). Moreover, fine rice particularly the aromatic rice costs 2-3 times higher than the coarse rice (Biswas et al., 1992). In 1997, AfricaRice and the National Agricultural Research Institute of Senegal (ISRA) have developed three aromatic rice varieties (Sahel 177, 328 and 329), well appreciated and released later in Senegal, Mali and Mauritania. There's evidence that, these local aromatic varieties can improve market penetration and increase local farmers profit (Rizzotto and Demont, 2010). However diminishing the production costs can effectively improve their competitiveness against imported rice (Demont et al., 2013). Nitrogen and phosphorus deficiencies in soils are the main factors limiting rice production in the Senegal River Valley (Haefele et al., 2002; Bado et al., 2008). As consequence, many farmers use only N and P fertilizers as urea and diammonium phosphate in the Senegal River valley (SRV). They don't give priority to K fertilizer because they estimate on the one hand that the soil-K reserves would be sufficient for decades, in other hand the high cost of K fertilizer makes it less interesting for farmers (Haefele, 2004). Besides, rice straw rich in K is completely removed from fields at the end of season by most of rice farmers in the SRV and used as cattle fodder. However Potassium (K) is essential for most of the biochemical and physiological processes that affect plant development and contribute to

the resistance of rice plants to various abiotics stresses such as lodging, salinity, cold, etc (Wang et al., 2013).

The aforementioned studies indicate that rice yield-nitrogen production functions exhibit substantial variation between genotypes, different locations and under different management conditions. Very few researches studied the effects of nitrogen fertilizer on paddy yield and nitrogen use efficiency (NUE) of the newly released aromatic rice varieties. Therefore, agronomic characterization of the newly released varieties is recommended, mostly optimum nitrogen fertilizer rate under each variety because nitrogen is the most important input for improving the productivity of aromatic rice. The present study aimed to characterize some newly released aromatic rice varieties for higher yield and NUE under optimum nitrogen fertilizer rates in the Senegal River Valley.

MATERIAL AND METHODS

Experimental sites

The study was conducted on two sites in the Senegal River Valley (SRV) (Senegal, West Africa) during the hot and dry season 2012 (HDS2012) and wet season 2012 (WS2012). The experimental sites are located on two research stations of Africa Rice center (AfricaRice) at Ndiaye (16° 11' N, 16° 15'W) and Fanaye (16° 32' N, 15° 11'W). The study area is characterized by Sahelian climate with a long dry period from October to June and a short wet season from July to September. The highest temperatures are recorded in May and the lowers in December-January. Solar radiation and maximum temperatures peak values are higher at Fanaye than at Ndiaye. Rice double cropping is adopted in the Senegal River Valley and takes place from February to June in the hot dry season (HDS), and from August to November in the wet season (WS). At Ndiaye, the soil is constituted by deposits of marine origin resulting in a shallow saline ground water table of 20 dS m⁻¹ or more (Ceuppens, 2000). The soil is an orthothionic Gleysol, containing 40–54% clay, (smectite and kaolinite) with average permeability of 2.8 mm d⁻¹ (FAO, 2006; Haefele, 2001). At Fanaye station, the ground water is non saline and the water table is constantly below 3.0 m. The soil at the site is an eutric Vertisol, with 45% to 65% clay content and average permeability of 2.0 mm d⁻¹ (Samba Diène, 1998; Haefele, 2001).

Experimental design and agronomic practices

Field agronomic experiments were conducted during two consecutive seasons (HDS and WS) on the two sites. Each field experiment was implemented with ten fertilizer treatments and five rice varieties in three replications in a factorial design. The plant materials were composed of four aromatic rice varieties Pusa Basmati (IET-10364), Sahel 329 (WAS 169-B-B-2-9), Sahel 177 (WAS 197-B-6-3-11)

and Sahel 328 (WAS 197-B-4-1-5), and one non-aromatic variety Sahel 108 (IR 13240-108-2-3-3) as control. The four aromatic rice varieties are popular and gained wider acceptance in Senegal because of their aroma, flavor and grain qualities.

Two management options of fertilizers (MOF) considering that N fertilizer needs to be applied indisputably associated to P and/without P and potassium nutrients were evaluated:

- the MOF₁ (NP): Different levels of Nitrogen (N) 0, 60, 90, 120 and 150 kg/ha are combined with phosphorus (26 kg P/ha).
- the MOF₂ (NPK): Different levels of Nitrogen (N) 0, 60, 90, 120 and 150 kg N/ha are combined with phosphorus (26 kg P/ha) and potassium (50 kg K/ha).

Fertilizer levels were attributed to experimental main plots and the rice varieties were attributed to the subplots. Rice seedlings were transplanted at the rate of 25 hills/m². Crop management was adjusted to the farmers' practice. The NPK nutrients were applied in the form of urea, triple super phosphate (TSP) and potassium chloride (KCl). TSP and KCl were applied basally before transplanting. For all fertilizer treatments, 50% N, 100% P and 100% K were broadcast at 21 days after transplanting. The remaining N dose was split- applied at panicle initiation (25%) and 10 days before flowering (25%). Herbicide (61/h Propanyl) and manual weeding were used for weed control. Insecticides (Furadan) were sometimes used at 25 kg/ha for pest control at the start of tillering, maximum tillering, panicle initiation and flowering. A constant water layer of 5-10 cm was maintained during the whole cropping season. Rice grain yields were determined from a 4 m² harvest area in each plot at maturity and reported at a standard water content of 14% and yield components were analyzed. The agronomic nitrogen use efficiency (ANUE) and partial factor productivity of applied PFPN were calculated.

The experimental fields were kept free during one season (natural fallow) before implementing the experiments.

Statistical analysis

The statistical analyses of the data were done using the four factors: variety, site, season and fertilizer treatments. The analysis of variance (ANOVA) was used to analyses the main effects of the four factors and their interactions using the statistical SAS software (SAS Inst. 1995) and the means were discriminated using LSD at 5% of significance.

RESULTS AND DISCUSSION

Effect of nitrogen fertilizer on grain yield

Across genotypes, rice yield varied from 3.3 to 7.4 Mg/ha under N-P fertilizer and from 3.5 to 8 Mg/ha under N-P-K

fertilizer application at during WS and rice yield varied from 4.0 to 8.6 Mg/ha under N-P fertilizer and from 4.1 to 8.8 Mg/ha under N-P-K fertilizer application during the HDS at Ndiaye (Fig. 1). At Fanaye station, rice yield varied from 3.7 to 8.1 Mg/ha under N-P fertilizer and from 3.7 to 9 Mg/ha under N-P-K fertilizer application during WS and rice yield varied from 4.0 to 8.6 Mg/ha under N-P fertilizer and from 3 to 10.3 Mg/ha under N-P-K fertilizer application during the HDS (Fig. 2). Across locations and growing seasons, Pusa Bamati had the lowest grain yield under all nitrogen fertilizer rates whereas the greatest grain yield was obtained by Sahel 108 and Sahel 177. The interaction genotype vs nitrogen is not significant ($P=0.56$). During the WS under N-P fertilizer at Ndiaye, all rice varieties exhibited the maximum grain yield at 90 kg N/ha while they exhibited the highest yield under the fertilizer recommendation of 120 N under the N-P-K fertilizer except Sahel 177 which showed the maximum yield at 90 kg N/ha similar to the N-P fertilization. During the HSD at Ndiaye rice grain yield increased with nitrogen fertilizer under N-P and N-P-K fertilizations. The maximum yields were obtained under the highest fertilizer rate. In contrast at Fanaye, during the WS, grain yield increased with increasing N fertilizer applied rates under N-P and N-P-K combination except for Sahel 108 that obtained the highest grain yield at 90 kg N/ha under N-P fertilization. At the site, during the HDS except the Sahel 177 and Pusa Basmati, all genotypes obtained the highest yield with the 90 kg N under N-P-K fertilizer while under the N-P fertilizer, Sahel 108 had the highest yield at 90 kg N; Sahel 177, Sahel 328 and Pusa Basmati obtained the highest yield under 120 Kg N/ha Sahel 329 obtained the highest yield at the maximum applied nitrogen fertilizer (150 kg N/ha). However for maximizing rice yield, proper integrated crop management practices are very important and should be adopted.

Effect of growing season on the grain yield

Significantly higher grain yields were observed in dry season as compared to wet season ($p<0.0001$) and genotypes responded differently to the seasons as the interaction of genotype and season was highly significant ($p = 0.003$). Grain yield was greater in HDS than in the WS under the two fertilizer combinations. Under no nitrogen fertilizer, there was yield decrease for all rice varieties and the decrease was at its highest values of 58% for Sahel 328 under P fertilizer and 47% for Sahel 108 under P-K fertilizer. Relative to N-P fertilizer, yield increase averaged 27, 32, 36, 33 and 28% under 0, 60, 90, 120 and 150 kg N/ha respectively. Under N-P-K fertilization, grain yield increase was -26, 30, 31, 31 and 20% under the same nitrogen rates respectively. Yield reduction under no nitrogen fertilizer treatment from the HDS to the WS might be due to soil nutrient initial conditions during the HSD. Plants should

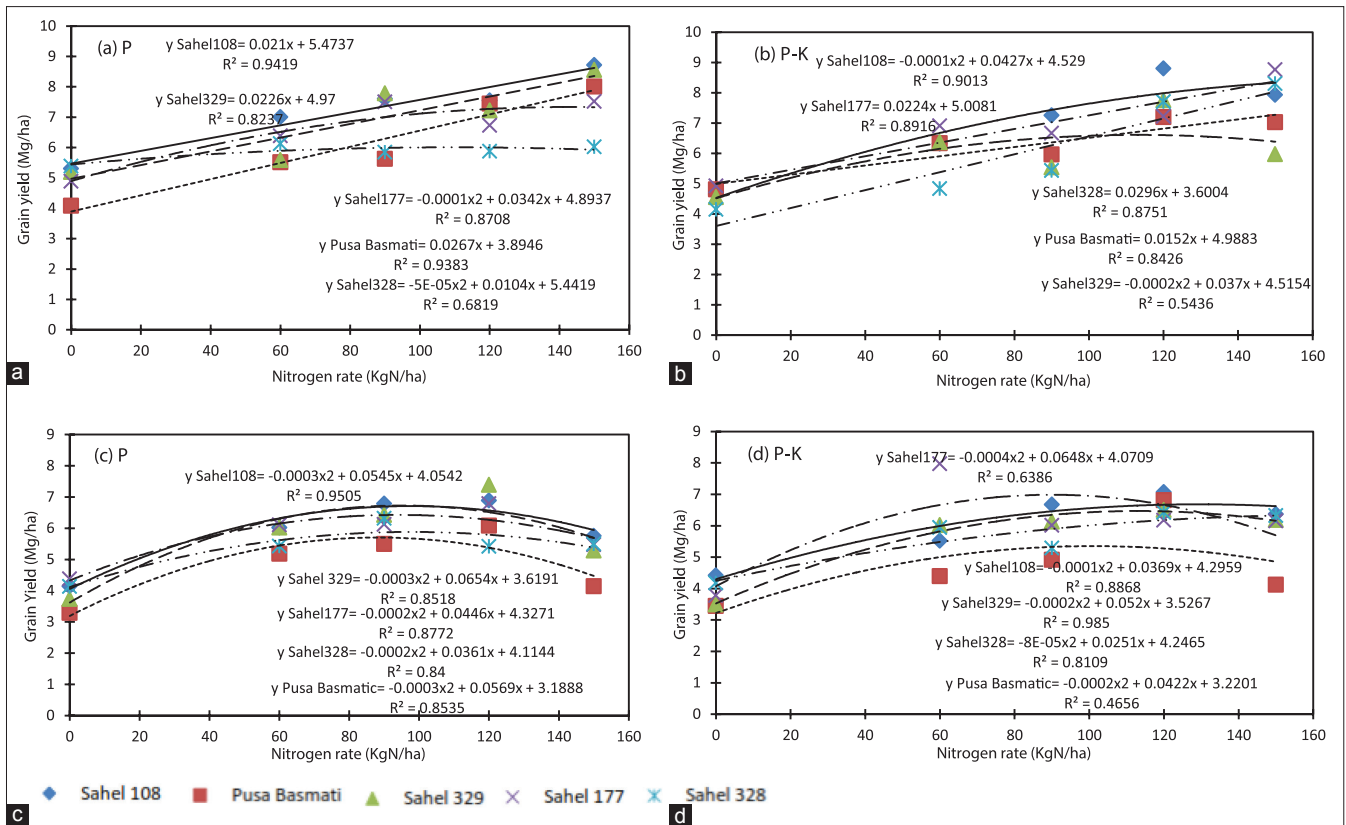


Fig 1. Response of rice varieties to N-P and N-P-K fertilizer during the HDS 2012 (a) and (b) and WS 2012 (c) and (d) at Ndiaye

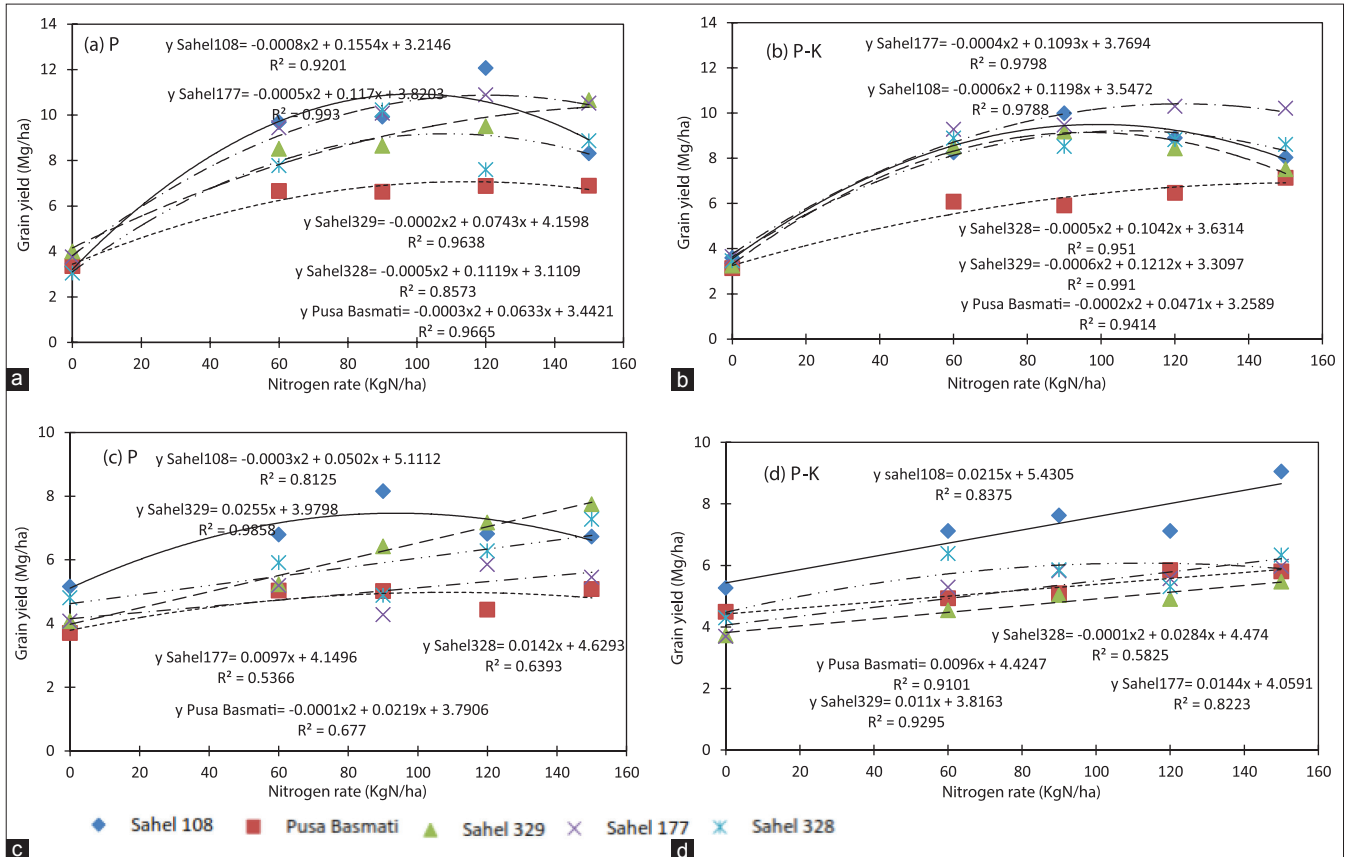


Fig 2. Response of rice varieties to N-P and N-P-K fertilizer during the HDS 2012 (a) and (b) and WS 2012 (c) and (d) at Fanaye

have taken advantage of the soil residual nitrogen level and the soil residual nitrogen must be very low at after the HDS due the plant nutrient uptake expressed by the higher yield. Over all nitrogen rates, yield increase under N-P fertilizer was 11, 20, 23, 38 and 10% for Sahel 108, Pusa Bamati, Sahel 328, Sahel 177 and Sahel 328, respectively. Under the N-P-K fertilizer, Sahel 108 grain yield decreased about 0.4% while yield increase was 35, 29, 34 and 20% for Pusa Bamati, Sahel 328, Sahel 177 and Sahel 328, respectively. The results of this study are similar to the finding of de Vries et al. (2010) whose data showed yield increase from HDS to WS from 24 to 230%, depending on treatments during experiments conducted at the same site. Traore et al. (2010) reported that rice yield was affected by the growing season with the highest yield occurring in the dry season. Similar trend in rice yield was reported by Bado et al. (2015). Higher yield in DS might be due to greater transpiration, greater spikelet production efficiency per unit biomass at reproductive phase and greater biomass accumulation from flowering to physiological maturity (Yang et al., 2008). Peng et al. (2004) reported positive correlation between grain yield of rice and the growth period daily mean radiation in dry season. Yang et al. (2008) indicated that grain yield and the yield gap between HDS and WS are affected by solar radiation during ripening stage. Spikelet sterility due to high daily temperature includes yield decline of rice (Matsui et al., 1997; Kim et al., 1996). Stuerz et al. (2014) reported highly significant correlations between meristem temperature at panicle initiation and spikelet fertility that could be a factor of yield decline in WS.

Rice response functions to fertilizer combination

Rice genotypes had different response functions to nitrogen fertilizer rate under P or P-K combinations as presented in Figs. 1 and 2 for each location and each season. Rice seasonal response function to fertilizer is also site dependent. At Ndiaye, aromatic rice yield increased linearly with nitrogen fertilizer rate under P and P-K addition during the HDS but quadratic relationship was observed between the rice yield and fertilizer combination during the WS. In contrast, at Fanaye, rice had quadratic relationship with nitrogen fertilizer rate during the HDS and linear relationship during the WS. Overall rice yield was high correlation coefficient with fertilizer combination with coefficients of determination that ranged from 0.47 to 0.99 at Ndiaye and from 0.53 to 0.99 at Fanaye. Better correlations were observed at Ndiaye under N-P combination while at Fanaye, the N-P-K combination had the highest correlation coefficients.

The two season pooled data (at Ndiaye and Fanaye) showed that under N-P fertilizer, Sahel 108 the most popular variety grown in the Senegal River Valley had the highest performance followed by Sahel 329, and Sahel 328. Pusa

Basmati had the poorest performance with the lowest yield. Under NPK fertilizer, the non-aromatic rice variety Sahel 108 still had the best performance followed by the aromatic variety Sahel 177 and Sahel 328 and Sahel 329; Pusa Basmati registered the poorest performance. The performance of varieties is shown through some agronomic traits of each of them. Even if Pusa Basmati had a relatively high panicle density, it had the lowest spikelet fertility, the lowest harvest index (Table 1). Among the aromatic rice varieties, Sahel 177 obtained the highest harvest index and the highest spikelet fertility after the non-aromatic check Sahel 108 (Table 1). Therefore the aromatic variety Sahel 177 could be the best choice of rice producers among the existing aromatic materials in the area in the Senegal River Valley.

In the light of these response functions, the recommended fertilizer rate should be used during the HDS to maximize grain yield at Ndiaye and during the WS at Fanaye while fertilizer rate should be 90 kg N/ha under K omission and the existing recommendation should be used for the N-P-K combination during the WS at Ndiaye. At Fanaye, the existing fertilizer NPK recommendation should be used under all rice genotypes except for the Sahel 177 and Pusa Basmati however; K can be omitted with no change in N and P. The comparison of five rice genotypes under similar fertilizer rate indicated that the check variety Sahel 108, is a confirmed high yielding variety with a yield potential of 12 Mg/ha that is the most popular variety used by producers in the Senegal River valley (Dingkuhn et al., 1995; Dingkuhn and Sow, 1997; de Vries et al., 2010). However, Sahel 177 was the competitive genotype against Sahel 108. The results of this study are similar to those of Ying et al. (1998) who showed that rice yield increased with increasing nitrogen rate for high-yielding rice genotypes in tropical and subtropical environments. Real time and site specific N recommendations should be applied (Mohammed et al., 2013). In other words, there is an inter-seasonal variability in rice genotype yield response to nitrogen rate even in the same environment due to influence of climatic factors and management practices on this relationship. In addition to inter-seasonal variability of the yield vs. nitrogen rate for the same locations, this relationship can vary substantially from one location to another due to influence of numerous factors, including climatic conditions, soil characteristics, management practices, and other factors. In addition, N recommendation should move from regional level to site-specific based on the residual soil nitrogen, soil P and K contents and yield target for more resources use efficiency with fewer effects on the environment (Ferguson et al., 2002; Djaman et al., 2013). Harell et al. (2011) reported linear response of rice to nitrogen rate below 150 kg N/ha and a plateau when the applied N rate is greater than 150 kg N/ha. Curvilinear response of rice yield to nitrogen was reported by Peng et al. (1999). Watkins et al.

Table 1: Effect of the two management options of fertilizers (MOF_g) on number of panicle per meter square (PAN), spikelet fertility (FER in %) and harvest index (HI in %)

Fertilizer treatments	Sahel 108			Pusa Basmati			Sahel 329			Sahel 177			Sahel 328		
	PAN	FER	HI	PAN	FER	HI	PAN	FER	HI	PAN	FER	HI	PAN	FER	HI
MOF 1: NP															
N (0 kg ha)	281 d	90.3 a	0.57 b	272 d	72.7 b	0.46 b	315 c	80.3 a	0.50 b	356 d	75.4 b	0.49 b	311 d	75.5 b	0.52 a
N (60 kg ha)	375 c	83.2 b	0.62 a	375 b	78.5 a	0.54 a	338 c	78.8 a	0.50 b	344 d	74.3 b	0.55 a	362 c	84.5 a	0.53 a
N (90 kg ha)	421 a	87.8 a	0.64 a	342 c	69.9 b	0.44 b	373 b	77.8 a	0.59 a	371 c	83.7 a	0.56 a	357 c	80.5 a	0.51 ab
N (120 kg ha)	423 a	83.8 b	0.63 a	418 b	65.3 b	0.45 b	406 a	76.0 ab	0.49 b	453 a	77.6 b	0.57 a	315 d	87.2 a	0.53 a
N (150 kg ha)	384 c	63.5 c	0.35 c	339 c	67.8 b	0.43 b	400 a	78.0 a	0.53 b	369	71.0 b	0.53 ab	367 c	75.4 b	0.48 b
MOF 2: NPK															
N (0 kg ha)	284 d	82.2 b	0.54 b	335 c	71.4 b	0.45 b	284 d	79.8 a	0.50 b	272 e	73.5 b	0.53 ab	330 d	76.3 b	0.52 a
N (60 kg ha)	396 b	84.9 b	0.60 a	322 c	68.4 b	0.33 c	339 c	77.5 a	0.54 ab	324 d	61.6 c	0.55 a	355 c	78.3 a	0.53 a
N (90 kg ha)	383 c	82.1 b	0.57 ab	395 b	67.9 b	0.44 b	375 b	78.6 a	0.47 b	352 d	73.1 b	0.51 b	338 d	76.3 b	0.53 a
N (120 kg ha)	415 a	86.6 a	0.59 a	405 b	63.1 c	0.42 b	386 b	72.0 b	0.49 b	389 c	71.2 b	0.55 a	449 b	68.8 c	0.49 ab
N (150 kg ha)	425 a	86.2 a	0.59 a	463 a	70.7 b	0.43 b	423 a	71.2 b	0.51 b	414 b	75.8 b	0.49 b	524 a	80.1 a	0.54 a

*On the same column, numbers followed by the same letters are statistically equal ($P \geq 0.05$)

Table 2: Rice partial factor productivity of applied nitrogen (PFPN) under N-P and N-P-K management

Locations	Seasons	N rates (kg N/ha)	N-P management					N-P-K management				
			Sahel 108	Pusa Basmati	Sahel 329	Sahel 177	Sahel 328	Sahel 108	Pusa Basmati	Sahel 329	Sahel 177	Sahel 328
Fanaye	HDS2012	60	161.3	110.9	141.8	157.3	129.4	137.6	101.3	141.8	154.7	148.2
		90	110.2	73.6	96.0	112.0	113.5	110.9	65.7	101.9	105.2	94.7
		120	100.5	57.3	79.1	90.7	63.2	74.1	53.8	70.3	85.8	73.5
		150	55.4	45.9	71.0	70.1	59.0	53.6	47.5	50.1	68.0	57.4
	WS2012	60	113.1	83.9	87.2	86.5	98.4	118.6	82.2	75.7	88.2	106.4
		90	90.5	55.7	71.3	47.5	54.2	84.7	56.6	56.0	64.6	65.1
		120	56.7	36.9	59.7	48.8	52.3	59.3	48.7	40.9	46.4	44.2
		150	44.9	33.9	51.6	36.3	48.5	60.3	38.7	36.5	39.8	42.2
Ndiaye	HDS2012	60	116.7	91.8	93.1	106.4	102.0	105.2	105.5	106.1	115.0	80.5
		90	84.5	62.5	86.5	83.3	64.9	80.5	66.2	61.5	74.1	60.4
		120	62.9	62.1	60.2	56.0	49.0	73.3	60.0	64.6	60.2	64.2
		150	58.1	53.4	57.0	50.1	40.1	52.9	46.9	39.8	58.4	55.4
	WS2012	60	100.3	86.4	100.3	101.8	90.4	92.0	73.2	100.2	132.8	99.0
		90	75.4	61.0	71.3	68.0	70.2	74.1	54.6	68.0	66.8	58.7
		120	57.4	50.7	61.6	56.5	45.1	58.9	56.7	54.2	51.4	53.5
		150	38.3	27.6	35.2	36.5	36.6	42.5	27.5	41.2	41.0	42.1

(2009) reported four different yield response functions on potential N response functions (quadratic, quadratic-plus-plateau, linear-plus-plateau, and Mitscherlich) estimated depending on location and year.

Partial factor productivity of applied nitrogen

The partial factor productivity of applied nitrogen fertilizer (PFPN) (also called nitrogen use efficiency or NUE) is the ratio of grain yield to N applied and it provides an integrative index that quantifies total economic output relative to utilization of all N resources in the system, including indigenous soil N and fertilizer N (Cassman et al., 1996). Nutrient response in terms of partial factor productivity decreased progressively with incremental levels of N from 60 to 150 kg N/ha. Partial factor productivity of applied N was influenced by different genotype and soil conditions and varied from 161 to 28 kg grain/kg N (Table 2). Pusa Basmati obtained the lowest PFPN under

all fertilizer rates and the highest PFPN was obtained by non-aromatic rice Sahel 108 followed by the aromatic rice Sahel 177. There were reduction of 3.6, 0.9 and 9.3% with K addition compared with N-P fertilizer for Sahel 108, Pusa Basmati and Sahel 329. In contract there were increases in PFPN by 3.7 and 2.6% with N-P-K for Sahel 177 and Sahel 328. PFPN showed seasonal variability. There was decrease in NUE of 33% under N-P and 29 % under N-P-K at Fanaye. The PFPN reduction was only 12 and 10% at Ndiaye under the same fertilizer combinations. Seasonal variation in PFPN could be due to the soil nutrient status before the installation of the experiment and the local environment might have impacted grain yield more than only N fertilizer application. The results of this study are closely in agreement with Haefele et al. (2003) who reported PFPN that varied from 33 and 140 kg grain kg⁻¹ N for Sahel 108, Jaya and IR50. Zhao et al. (2010) reported PFPN range of 24 - 61 kg grain kg⁻¹ N applied under traditional

flooding and 26 to 86 kg grain kg⁻¹ N applied under system of rice intensification. Peng et al. (2010) report rice PFPN that ranged from 36.3 to 64 kg grain kg⁻¹ N.

Agronomic nitrogen use efficiency (ANUE)

Agronomic nitrogen use efficiency (ANUE) varied with rice variety with seasons and location. At Ndiaye ANUE varied from 4.1 to 34.5 kg grain/kg N during the HDS and from 4.4 to 69.9 kg grain/kg N during the WS (Table 3). On all nitrogen rates average, ANUE was 23.4, 23.7, 18.6, 21.7, and 6.4 kg grain/kg N under P addition and 28.2, 18.1, 19.4, 24.3 and 10.7 kg grain/kg N under P-K addition for Sahel 108, Pusa Basmati, Sahel 329, Sahel 177 and Sahel 328, respectively. K addition to N-P significantly increased ANUE from 6.4 to 20.78 kg grain/kg N which represented 225% for Sahel 108 while the increase was very slight for other varieties Pusa Basmati obtained the lowest ANUE and the highest ANUE was obtained by Sahel 108 under NPK combination. None of the varieties had the monotonous trend in the ANUE under all nutrient combination during the HDS. During the WS at Ndiaye, rice ANUE decreased with increasing nitrogen rate under P and P-K additions. Over all nitrogen rates average, ANUE was 23.6, 21.3, 27.2, 18.9, and 16.4 kg grain/kg N under P addition and 19.6, 16.1, 28.6, 32.6 and 18.7 kg grain/kg N under P-K addition for Sahel 108, Pusa Basmati, Sahel 329, Sahel 177 and Sahel 328, respectively (Table 3). For a comparison of N-P and N-P-K, Sahel 177 was revealed to have the highest increase in ANUE (+13.6 kg grain/kg) due to K addition while Sahel 108 and Pusa Basmaty obtained ANUE decrease of 4 and 5 kg grain/kg, respectively with K addition to N-P. Rice variety Sahel 329 obtained the highest ANUE under all fertilizer rates, followed by Pusa Basmati. Sahel 328 always obtained the lowest ANUE.

At Fanaye, during the HDS, ANUE varied 23.6 to 105.9 kg grain/kg N under N-P and from 26.6 to 93.9 kg grain/kg N and from 0.9 to 33.2 kg grain/kg N and from 6.7 to 34.9 kg grain/kg N under N-P-K during the WS (Table 3). Overall, Pusa Basmati had the lowest ANUE during both seasons and under both fertilizer combinations and both Sahel 108 and Sahel 177 had the highest ANUE. During the HDS, rice ANUE decreased with increasing Nitrogen rate under P and P-K additions. During the WS, different trends in rice ANUE were observed. ANUE decreased with N fertilizer up to 120 kg/ha for Pusa Basmati, Sahel 177, and Sahel 328 under N-P and for Sahel 108 and Sahel 328 under N-P-K and the ANUE increased for the nitrogen fertilizer rate greater than 120 kg/ha. Monotonous decreasing trend was observed for Sahel 108 under N-P and for Sahel 177 and Sahel 329. Under N-P, Sahel 329 ANUE increased with N rate from 18.3 to 25.5 and decreased thereafter to 24.5 under 150 kg N/ha. Overall, Sahel 177 was revealed to have the highest ANUE among the aromatic rice varieties grown at Fanaye under N-P-K fertilization. Under N-P fertilizer, Sahel 329 and Sahel 177 were the best choice in the terms of ANUE at Fanaye. There was decrease in ANUE under NPK relative to NP of 3.6 15.9, 1.4, and 4.4 kg grain/kg N for the Sahel 108, Sahel 329, Sahel 177 and Sahel 328 respectively while only Pusa Basmati obtained an increase of 3.1 kg grain/kg N during the HDS. During the WS, there were increases of 14.7 and 6.0 kg grain/kg N for Sahel 108 and the aromatic rice Sahel 177. In contrast, ANUE of Pusa Basmati, Sahel 329 and Sahel 328 decreased by 0.5, 12.8 and 2.8 kg grain/kg N under NPK compared to NK. Therefore Sahel 177 should be proposed at Fanaye among the studied aromatic rice varieties for increasing rice ANUE and the potassium could be omitted with any yield reduction. The Soil at Fanaye should have high

Table 3: Rice agronomic nitrogen use efficiency (ANUE) under N-P and N-P-K management

Locations	Seasons	N rates (kg N/ha)	N-P management					N-P-K management				
			Sahel 108	Pusa Basmati	Sahel 329	Sahel 177	Sahel 328	Sahel 108	Pusa Basmati	Sahel 329	Sahel 177	Sahel 328
Fanaye	HDS2012	60	105.9	55.1	75.3	94.7	78.6	77.9	49.0	87.7	93.9	90.6
		90	73.3	36.4	51.6	70.3	79.6	71.1	30.9	65.8	64.7	56.3
		120	72.8	29.4	45.8	59.4	37.8	44.3	27.7	43.2	55.4	44.7
		150	33.2	23.6	44.3	45.1	38.7	29.7	26.6	28.4	43.7	34.3
	WS2012	60	27.2	22.2	19.4	18.8	18.3	30.8	7.3	13.6	26.6	34.9
		90	33.2	14.6	26.1	2.3	0.9	26.1	6.7	14.6	23.6	17.4
		120	13.8	6.1	25.8	14.9	12.3	15.4	11.3	9.8	15.6	8.5
		150	10.5	9.2	24.5	9.2	16.4	25.2	8.7	11.7	15.2	13.6
Ndiaye	HDS2012	60	28.3	23.8	6.5	25.0	12.2	27.7	25.3	30.3	33.0	11.4
		90	25.5	17.1	28.7	29.1	5.1	28.8	12.8	11.0	19.4	14.3
		120	18.7	28.0	16.9	15.3	4.1	34.5	19.9	26.7	19.2	29.7
		150	22.8	26.2	22.4	17.6	4.2	21.8	14.8	9.5	25.6	27.7
	WS2012	60	31.3	31.6	38.1	28.9	21.6	18.4	15.8	42.1	69.9	29.4
		90	29.4	24.5	29.8	19.5	24.3	25.0	16.3	29.3	24.8	12.3
		120	22.9	23.3	30.4	20.1	10.7	22.1	28.0	25.1	19.9	18.8
		150	10.8	5.7	10.3	7.3	9.1	13.0	4.5	17.9	15.8	14.3

potassium content that allows omission of this nutrient without any impact on rice grain yield. The aromatic rice varieties Sahel 177, Sahel 328, and Sahel 329 are making rapid headway in Senegal (Tollens et al., 2013) and need to improve to their competitiveness against the imported rice. The results of this study are in agreement with de Vries et al. (2010) who reported ANUE of rice variety Sahel 108 for the same experimental sites within the range of 30 – 77 kg grain/kg N depending on the irrigation regime, and location. Xie et al. (2007) reported a decreasing ANUE with N fertilizer and the ANUE of 8.02~20.14 kg/kg and 3.4~18.37 kg/kg in rice varieties Jinzao22 and Shanyou63 in Zhejiang (China), respectively. Stuerz et al. (2014) reported that lower spikelets number per panicle and spikelet fertility are the main attributes to the largest yield gap at the same research site. [Cassman et al. \(1998\)](#) indicated that the intrinsic capacity of wetland rice systems to conserve N and the rapid N uptake potential of the rice plant provide opportunities for significant increases in N efficiency by improved management and monitoring of indigenous N resources, straw residues, plant N status, and N fertilizer.

SUMMARY AND CONCLUSION

Four aromatic rice varieties and one non-aromatic variety were used to study the effect of Nitrogen fertilizer on rice grain yield and partial factor productivity of nitrogen (PFPN) and agronomic nitrogen use efficiency (ANUE) under potassium omission management.

Results showed that across genotypes, rice yield increased with nitrogen application. Sahel 108 and Sahel 177 obtained the highest yield across locations and growing seasons. Sahel 177 consistently showed the highest yield at 90 kg N/ha under all fertilizer managements. Rice genotypes had different response functions to nitrogen fertilizer rate under P or P-K combinations and were also site dependent. Rice PFPN and ANUE were influenced by genotype, location, and season. Sahel 177 obtained the highest PFPN and the highest ANUE among all the aromatic rice varieties. Potassium addition to nitrogen and phosphorus fertilizers increased nitrogen use efficiency. From the results of the study, the aromatic rice variety Sahel 177 is the performing alternative to the non-aromatic rice Sahel 108 in terms of high yield potential and because of the high pricing of the aromatic rice and its preference by consumers, Sahel 177 represents a great opportunity for rice producers in the Senegal River Valley at 90 kg N/ha in addition to P-K recommended rates.

Author contributions

B.V.B.: designed and supervised the experiment, reviewed the manuscript. V.C.M.: conducted field experiments and

collected data. K.D.: analyzed the data and wrote the manuscript.

REFERENCES

- Ahmad, A., A. Hussain, S. Iqbal and Z. Husnain. 2005. [Growth, radiation use efficiency and paddy yield of fine rice \(Super basmati\) as affected by sowing date and split nitrogen application](#). In: *Proceedings of the International Seminar on Rice Crop*. October 2-3, 2005. RRI, Lahore Pakistan. p315-321.
- Bado, V. B., K. Djaman, V. C. Mel, D. A. Bama Nati, A. B. Balde, B. Manneh S. Irmak and K. Futakuchi. 2015. [Agronomic performance of salt-tolerant rice genotypes in salt-affected soil under integrated management options of nitrogen, zinc, and gypsum](#). *Eur. J. Agron.*
- Biswas, S. K., B. Banu, K. A. Kabir, F. Begum and N. H. Choudhury. 1992. [Physicochemical properties of modern and local rice varieties of Bangladesh](#). *Bangladesh Rice J.* 3(1&2): 128-131.
- Bray, R. H. and L. T. Kurtz. 1945. [Determination of total, organic, and available forms of phosphorus in soils](#). *Soil Sci.* 59: 39-45.
- Bremner, J. M. 1965. [Inorganic forms of nitrogen](#). *Agronomie.* 9: 1179-237.
- Cassman, K. G., A. D. Dobermann, D. Walters and H. Yang. 2003. [Meeting cereal demand while protecting natural resources and improving environmental quality](#). *Ann. Rev. Environ. Res.* 28: 315-358.
- Cassman, K. G., G. C. Gines, M. A. Dizon, M. I. Samson and J. M. Alcantara. 1996. [Nitrogen-use efficiency in tropical lowland rice systems: contributions from indigenous and applied nitrogen](#). *Field Crops Res.* 47: 1-12.
- Cassman, K. G., S. Peng, D. C. Oik, J. K. Ladha, W. Reichardt, A. Dobemann and U. Singh 1998. [Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems](#). *Field Crops Res.* 56: 7-39.
- Ceuppens, J. 2000. [Water and Salinity Management for Irrigated Rice in the Senegal River Delta](#). Departement Landbeheer. Katholieke Universiteit Leuven, Leuven.
- Das, T. and M. A. Baqui, 2000. [Aromatic Rices of Bangladesh](#). *Aromatic Rices*. Oxford & IBH Publishing Co., Pvt., Ltd., New Delhi, India. Pp. 184-187.
- de Vries, E. M., J. Rodenburg, B. V. Bado, A. Sow, P. A. Leffelaar and K. E. Giller. 2010. [Rice production with less irrigation water is possible in a Sahelian environment](#). *Field Crops Res.* 116: 154-164.
- Demont, M., P. Rutsaert, M. Ndour, W. Verbeke, P. A. Seck and E. Tollens. 2013. [Experimental auctions, collective induction and choice shift: Willingness-to-pay for rice quality in Senegal](#). *Eur. Rev. Agric. Econ.* 40(2): 261-286.
- Dingkuhn, M. and A. Sow. 1995. [Potential yields of irrigated rice in the Sahel](#). In: *Irrigated Rice in the Sahel: Prospects for Sustainable Development*. WARDA, Bouaké, Pp. 361-379.
- Dingkuhn, M. and A. Sow. 1997. [Potential yields of irrigated rice in the Sahel](#). In: *Miézan, K.M., M. C. S. Wopereis, M. Dingkuhn, J. Deckers, T. F. Randolph, (Eds.), Irrigated Rice in the Sahel: Prospects for Sustainable Development*. WARDA, Bouaké, Côte d'Ivoire. Pp. 361-379.
- Dingkuhn, M., A. Sow, A. Samba, S. Diack and F. Asch. 1995. [Climatic determinants of irrigated rice performance in the Sahel. I. Photothermal and micro-climatic responses of flowering](#). *Agric. Syst.* 48: 435-456.

- Djaman, K., S. Irmak, D. L. Martin, R. B. Ferguson and M. L. Bernards. 2013. Plant nutrient uptake and soil nutrient dynamics under full and limited irrigation and rainfed. *Maize Prod. Agron. J.* 105: 527-538.
- Dunn, D. and G. Stevens. 2006. University of Missouri soil test recommendations for rice production. In: Dickens, C. and D. Beighley, (Eds.), *Missouri Rice Research Update 2005*. Southeast MO State University. Special Report 001. Pp. 64-65.
- Fageria, N. K., V. C. Baligar and C. A. Jones. 1997. *Growth and Mineral Nutrition of Field Crops*. 2nd ed. Marcel Dekker, New York.
- Fan, M., J. Shen, L. Yuan, R. Jiang, X. Chen and W. J. Davies. 2012. Food security. Improving crop productivity and resource efficiency to ensure food security and environmental quality in China. *J. Exp. Bot.* 63: 13-24.
- Farook, U., M. Iqbal and A. Bashir. 1999. Cost and revenue statistics of paddy production: Farmers' perspectives. *Int. J. Agric. Biol.* 1: 13-18.
- Ferguson, R. B., G. W. Hergert, J. S. Schepers, C. A. Gotway, J. E. Cahoon and T. A. Peterson. 2002. Site-specific nitrogen management of irrigated maize: Yield and soil residual nitrate effects. *Soil Sci. Soc. Am. J.* 66: 544-553.
- Gangaiah, B. and R. Prasad. 1999. Response of scented rice (*Oryza sativa*) to fertilizers. *Indian J. Agron.* 44(2): 294.
- Guindo, D., B. R. Wells and R. J. Norman. 1994. Cultivar and nitrogen rate influence on nitrogen uptake and partitioning in rice. *Soil Sci. Soc. Am. J.* 58: 840-845.
- Guo, C. H., Z. Q. Gao and G. Y. Miao. 2010. Effect of shading at post flowering on photosynthetic characteristics of flag leaf and response of grain yield and quality to shading in wheat. *Acta Agron. Sin.* 36: 673-679.
- Haefele, S. M., M. C. S. Wopereis, M. K. Ndiaye and M. J. Kropff. 2003. A framework to improve fertilizer recommendations for irrigated rice in West Africa. *Agric. Syst.* 76: 313-335.
- Haefele, S. M. 2001. Improved and sustainable nutrient management for irrigated rice-based cropping systems in West-Africa. *Hamburger Bodenkundliche Arbeiten*. Universitat Hamburg, Hamburg. p. 241.
- Harrell, D. L., B. S. Tubaña, J. Lofton and Y. Kanke. 2011. Rice response to nitrogen fertilization under stale seedbed and conventional tillage systems. *Agron. J.* 103: 494-500.
- Hasegawa, T., Y. Koroda, N. G. Seligman and T. Horie. 1994. Response to spikelet number of plant nitrogen concentration and dry weight in paddy. *Agron. J.* 86: 673-676.
- Helmke, P. A. and D. L. Sparks. 1996. Lithium, sodium, potassium, rubidium, and cesium. In: Sparks, D. L. (ed.), *Methods of Soil Analysis. Part. 3. Chemical Methods*. SSSA Book Series No. 5. SSSA and ASA, Madison, WI. Pp. 551-574.
- Jashim, C., U. Ahmed and K. U. Ahmed. 1984. Response of rice varieties to applied N in saline soils. *Int. Rice Res. Newsl.* 9(5): 22.
- Kim, H. Y., T. Horie, H. Nakagawa and K. Wada. 1996. Effects of elevated CO₂ concentration and high temperature on growth and yield of rice: II. The effect on yield and its components of Akihikari rice. *Jpn. J. Crop Sci.* 65: 644-651. (in Japanese with English Abstract).
- Zhao, L., L. Wu, C. Dong and Y. Li. 2010. Rice yield, nitrogen utilization and ammonia volatilization as influenced by modified rice cultivation at varying nitrogen rates. *Agric. Sci.* 1: 10-16.
- Mannan, M. A., M. S. U. Bhuiya, H. M. A. Hossain and M. I. M. Akhand. 2010. Optimization of nitrogen rate for aromatic basmati rice (*Oryza sativa* L.). *Bangladesh J. Agric. Res.* 35: 157-165.
- Matsui, T., O. S. Namuco, L. H. Ziska and T. Horie. 1997. Effects of high temperature and CO₂ concentration on spikelet sterility in indica rice. *Field Crops Res.* 51: 213-219.
- Mohammed, Y. A., J. Kelly, B. K. Chim, E. Rutto, K. Waldschmidt and J. Mullock. 2013. Nitrogen fertilizer management for improved grain quality and yield in winter wheat in Oklahoma. *J. Plant Nutr.* 36: 749-761.
- Norman, D., R. Janke, S. Freyenberger, B. Schurle and H. Kok. 1997. *Defining and Implementing Sustainable Agriculture*. Kansas Sustainable Agriculture Series, Paper #1. Kansas State University, Manhattan, KS.
- Norman, R. J., C. E. Wilson, N. A. Jr. Slaton, K. A. K. Moldenhauer, D. L. Boothe, S. D. Clark and A. D. Cox. 2000. Grain yield response of new rice cultivars. In: Norman, R. J. and C. A. Beyrouty, (Eds.), *Arkansas Rice Research Studies 1999*. Ark. Agric. Exp. Stn. Res. Ser. 476: 267-271.
- Peng, S., R. J. Buresh, J. Huang, X. Zhong, Y. Zou, J. Yang, G. Wang, Y. Liu and R. Q. Hu. 2010. Improving nitrogen fertilization in rice by site-specific N management: A review. *Agron. Sust. Dev.* 30: 649-656.
- Peng, S., K. G. Cassman, S. S. Virmani, J. Sheehy and G. S. Khush. 1999. Yield potential trends of tropical rice since the release of IR8 and the challenge of increasing rice yield potential. *Crop Sci.* 39: 1552-1559.
- Peng, S., J. Huang, J. E. Sheehy, R. C. Laza, R. M. Visperas, X. Zhong, G. S. Centeno, G. S. Khush and K. G. Cassman. 2004. Rice yields decline with higher night temperature from global warming. *Proc. Nat. Acad. Sci. U.S.A.* 101(27): 9971-9975.
- Peng, S., J. Huang, J. E. Sheehy, R. C. Laza, R. M. Visperas, X. Zhong, G. S. Centeno, G. S. Khush and K. G. Cassman. 2004. Rice yield decline with higher night temperature from global warming. In: Redona, E. D., A. P. Castro and G. P. Llanto, (Eds.), *Rice Integrated Crop Management: Towards a Rice Check System in the Philippines*, Nueva Ecija, Philippines, Phil Rice. Pp. 46-56.
- Peng, S., Q. Tang and Y. Zou. 2009. Current status and challenges of rice production in China. *Plant Prod. Sci.* 12: 3-8.
- SAED. 2011. *Recueil des Statistiques de la Vallée du Fleuve Sénégal*. Senegal.
- Samba, D. R. 1998. *Riziculture et dégradation des sols en vallée du fleuve Sénégal: Analyse comparée des fonctionnements Hydro-salins des sols du delta et de la moyenne vallée en simple et double riziculture*. Thèse de Doctorat, Université Cheikh Anta Diop, Dakar, Sénégal. p. 221.
- SAS Institute Inc. 2003. *SAS Online Doc® 9.1*. SAS Institute, Inc., Cary, NC.
- Seck, P. A., E. Tollens, M. C. S. Wopereis, A. Diagne and I. Bamba. 2010. Rising trends and variability of rice prices: Threats and opportunities for Sub-Saharan Africa. *Food Policy.* 35(5): 403-411.
- Shivay, Y. S., R. Prasad and A. Rahal. 2010. Genotypic variation for productivity, zinc utilization efficiencies and kernel quality in aromatic rice under low available zinc conditions. *J. Plant Nutr.* 33(12): 1835-1848.
- Snyder, C. S. and N. A. Slaton. 2002. Rice production in the United States - An overview. *Better Crops.* 16: 30-35.
- Stuerz, S., A. Sow, B. Muller, B. Manneh and F. Asch. 2014. Yield components in response to thermal environment and irrigation system in lowland rice in the Sahel. *Field Crops Res.* 163: 47-54.
- Tollens, E., M. Demont, M. Sié, A. Diagne, K. Saito and M. C. S. Wopereis. 2013. From WARDA to AfricaRice: An Overview of Rice Research for Development Activities Conducted in

- Partnership in Africa. CABI. (H ISBN 9781845938123.
- Traoré, K., B. V. Bado, T. Guèye and S. Gaye. 2010. Grain yield performance of interspecific irrigated rice genotypes in the senegal river valley, as affected by the cropping seasons. *West Afr. J. Appl. Ecol.* 17: 65-80.
- USAID. 2009. Global Food Security Response: Senegal Rice Study. United States Agency for International Development (USAID), Washington, D.C., USA.
- Walkley, A. and I. A. Black. 1934. An examination of the Degtjareff method for determining organic carbon in soils: Effect of variations in digestion conditions and of inorganic soil constituents. *Soil Sci.* 63: 251-263.
- Wang, Y. Y., B. Zhu, Y. Shi and C. S. Hu. 2008. Effect of nitrogen fertilization on upland rice based on pot experiments. *Commun. Soil Sci. Plan* 39(11-12): 1733-1749.
- Watkins, K. B., J. A. Hignight, R. J. Norman, T. L. Roberts, N. A. Slaton, C. E. Wilson and D. L. Frizzell. 2009. Comparison of economic optimum nitrogen rates for rice in arkansas. *Agron. J.* 102: 1099-1108.
- Xie, L. L., H. X. Weng, C. L. Hong and A. L. Yan. 2007. Uptake of bokchoy and *Ipomoea aquatica* Forsk to iodine species. *Plant Nutr. Fertil. Sci.* 13(1): 123-128.
- Yang, C., D. Shi and D. Wang. 2008. Comparative effects of salt and alkali stresses on growth, osmotic adjustment and ionic balance of an alkali-resistant halophyte *Suaeda glauca* (Bge.). *Plant Growth Regul.* 56: 179-190.
- Ying, J., S. Peng, G. Yang, N. Zhou, R. M. Visperas and K. G. Cassman. 1998. Comparison of high-yield rice in tropical and subtropical environments: II. Nitrogen accumulation and utilization efficiency. *Field Crops Res.* 57: 85-93.
- Yoshida, H., T. Horie and T. Shiraiwa. 2006. A model explaining genotypic and environmental variation of rice spikelet number per unit area measured by cross-locational experiments in Asia. *Field Crops Res.* 97: 337-343.