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Effects of Alternate Wetting and Drying Irrigation Regime and Nitrogen Fertilizer on Yield and Nitrogen Use Efficiency of Irrigated Rice in the Sahel

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Abstract: The objectives of this study were to investigate water saving strategies in the paddy field and to evaluate the performance of some of the newly released rice varieties. Field experiments were conducted at Fanaye in the Senegal River Valley during two rice growing seasons in 2015. Three irrigation regimes ((i) continuous flooding, (ii) trigging irrigation at soil matric potential (SMP) of 30 kPa, (iii) trigging irrigation at SMP of 60 kPa) were tested in an irrigated lowland rice field. Irrigation regimes (ii) and (iii) are alternate wetting and drying (AWD) cycles. Four inbred rice varieties (NERICA S-21, NERICA S-44, Sahel 210 and Sahel 222) and one hybrid rice (Hybrid AR032H) were evaluated under five nitrogen fertilizer rates (0, 50, 100, 150 and 200 kg N ha^{-1}). The results showed that rice yield varied from 0.9 to 12 t ha^{-1}. The maximum yield of 12 t ha^{-1} was achieved by NERICA S-21 under AWD 30 kPa at 150 kg N ha^{-1}. The AWD irrigation management at 30 kPa resulted in increasing rice yield, rice water use and nitrogen use efficiency and reducing the irrigation applications by 27.3% in comparison with continuous flooding. AWD30 kPa could be adopted as a water saving technology for water productivity under paddy production in the Senegal River Middle Valley. Additional research should be conducted in the upper Valley, where soils are sandier and water is less available, for the sustainability and the adoption of the irrigation water saving practices across the entire Senegal River Valley.

Keywords: rice; alternate wetting and drying; nitrogen fertilizer; yield; nitrogen use efficiency

1. Introduction

Irrigation water is becoming increasingly scarce, particularly in Sahel environments similar to the Senegal River Valley, where long-term average annual precipitation is less than 300 mm [1] and where rice production remains one of the main agricultural activities under double crop production practices [2]. Rice potential yields as high as 12 t ha^{-1} under effective irrigation management can be achieved in this soil and climate with good crop and resources management conditions [3–5]. Actual paddy yield in the valley is about 6–6.5 t ha^{-1} on the Senegal side [6,7] and within the range of

3.3 to 4.6 t ha^{-1} in Mauritania [8,9]. In the Senegal River Valley, daily grass reference evapotranspiration (ETo) can reach a maximum of 10 mm/day [10]. Continuous flooded irrigated rice seasonal crop actual evapotranspiration (ETa) can range from 632 to 929 mm, while the seasonal irrigation water requirement in the region can vary between 863 and 1198 mm; both ETa and irrigation requirements exhibit seasonality [10].

It has been reported that rice yield decreases with the default of good agricultural management practices and inappropriate irrigation management [6,11,12], resulting in an increase of soil salinity in the Senegal River Delta areas [13]. Irrigation requirements are a major contributor to rice production cost because the cost of pumping water is high, accounting for about 28% of operating cost [9]. Under climate change, there is a need to adopt sustainable production and water saving technologies to reduce pumping cost without yield penalty. Water saving technologies have been developed and implement under paddy production contrary to continuous flooding, as reported by Tuong and Bhuiyan [14] and Li [15], and the Alternate Wetting and Drying (AWD) irrigation technology adoption is increasing throughout different climate and agro-ecological zones [3,15–19].

One water saving technology, known as Alternate Wetting and Drying (AWD), was developed by the International Rice Research Institute (IRRI) and implemented through several studies with seasonal irrigation water saving of up to 44% [3,20,21]. Tan et al. [19] reported no significant yield penalty under AWD and an increase in water productivity by 17% as compared with continuous flooding irrigation treatment. AWD reduces seasonal irrigation water supply, and improves water use efficiency and yield. Under decreasing fresh water resources used for food production in the semiarid environment similar to the Senegal River Valley [7], coupled with high daily peak reference evapotranspiration [1] and a rice daily actual evapotranspiration of 14 mm [10], AWD technology should be of high importance for paddy rice water productivity improvement in the Senegal River Valley. Yang and Zhang [22] reported increase in paddy yield under AWD due to the increase of the proportion of productive tillers, reduction in the angle of the topmost leaves allowing more light penetration into the canopy, and change in shoot and root activity. Rejesus et al. [20] found a 38% reduction in irrigation hours the application of AWD without any significant rice yields and profits penalty. Zhang et al. [23] also indicated irrigation water saving of 35% under AWD with a 10% yield increase relative to continuous flooding. LaHue et al. [24] observed no yield difference between the continuous flooding and the AWD treatments. Increase in water productivity associated with the adoption of the AWD technology was observed by Li and Barker [25]. However, Sudhir-Yadav et al. [26] reported slight yield reduction under AWD, while Xu et al. [27] observed yield reduction as high as 16%. Howell et al. [28] reported no significant difference in rice yield between AWD and CF with 57% of irrigation water saving under AWD in Agyauli in the central Terai region of Nepal when comparing two rice cultivars of Hardinath-1 and CH-45. Richards and Sander [29] indicated that AWD allows 30% reduction in seasonal irrigation amount with no yield penalty for most lowland rice varieties. Devkota et al. [30] reported irrigation water reduction to only 30% of the irrigation requirements under CF. However, they reported yield reduction of 27 and 40% under AWD during two-year research in north-western Uzbekistan.

While the AWD practice has been demonstrated to provide advantages in terms of reducing water supply and increasing crop productivity, very few studies have been conducted to evaluate potential water saving strategies, especially under different fertilizer application rates in the Senegal River Valley [3,31–33]. Nitrogen fertilizer is one of the most important nutrients that determine rice yields [34–37]. Harell et al. [37] reported linear response of rice to nitrogen rate below 150 kg N ha^{-1} and a plateau when the applied N rate is greater than 150 kg N ha^{-1}. Curvilinear response of rice yield to nitrogen applied rate was reported by Peng et al. [38] and Djaman et al. [39]. The nitrogen fertilizer applied rates that achieved maximum yield were 157 and 151 kg ha^{-1} under two tillage practices [37]. Nitrogen fertilizer recommendation rates have been developed and applied at regional level regardless of soil types, soil chemical and biological properties, and rice genotypes. Farmers used to apply higher rates of applied N fertilizer than the recommended amount, assuming that increasing N would always result in increasing crop yields [40], which can result in altering and negatively affecting the sustainability of the production system and increasing the production cost. Djaman et al. [39] found lower nitrogen fertilizer requirement (90 kg N ha^{-1}) for most of the aromatic rice varieties to achieve maximum yield, while the optimum nitrogen fertilizer for the non-aromatic rice varieties was 120 kg N ha^{-1}. Doberman et al. [41] and Wang et al. [42] reported that rice quality and yield were mostly affected by imbalanced nitrogen fertilizer application rate in soils. Cassman et al. [43] indicated that improvement in crop yields is attributed to the increase in fertilizer use, especially nitrogen fertilizer. In the dynamics of sustainable system intensification, there is a need for proper fertilizer and water management practices under changing climate [7].

The interaction of water and nitrogen fertilizer management under high yielding rice varieties and the hybrid rice should retain the attention of researchers and decision makers relative to the self-sufficiency program in rice and system sustainability for several sub-Saharan African countries, such as Senegal [44]. Thus, the objectives of this study were to investigate water saving strategies under different N fertilizer levels and quantify crop water use efficiency and nitrogen use efficiency in the paddy field and, to characterize some newly released high-yielding rice varieties in the Senegal River Valley.

2. Materials and Methods

2.1. Site Description

The study was conducted at AfricaRice Fanaye research station (16°32′ N, 15°11′ W) in Senegal during the hot and dry season (HDS) and wet season (WS) in 2015. The research site is characterized by a Sahelian climate with a short rainy season from July to early October and a dry period covering the rest of the year, and characterized by large annual amplitudes in temperature. Rice production takes place twice a year in the Senegal River Valley from February to June during the HDS, and from August to November in the WS. Weather variables such as wind speed, air temperature, relative humidity, solar radiation and precipitation (Figure 1) were measured over a well-watered grass surface, collected at the experimental site using automated weather station (CimAGRO) installed within the research station. The soil type at the experimental site is characterized as eutric Vertisol, with high clay content (45% to 65%), composed of kaolinite and smectite minerals [45,46]. Soil wilting point and field capacity are 0.25% and 0.44%, respectively, while soil porosity is 0.52%. Rice average rooting depth was 0.65 m under the deep water table at Fanaye. Total soil holding capacity is 286 mm for rice root zone, and the available water under non-flooded irrigation is 124 mm, while it is 176 mm under continuous flooding conditions. The ground water table at the site is usually below 3 m, and the percolation rate is 2.0 mm d^{-1} [46].

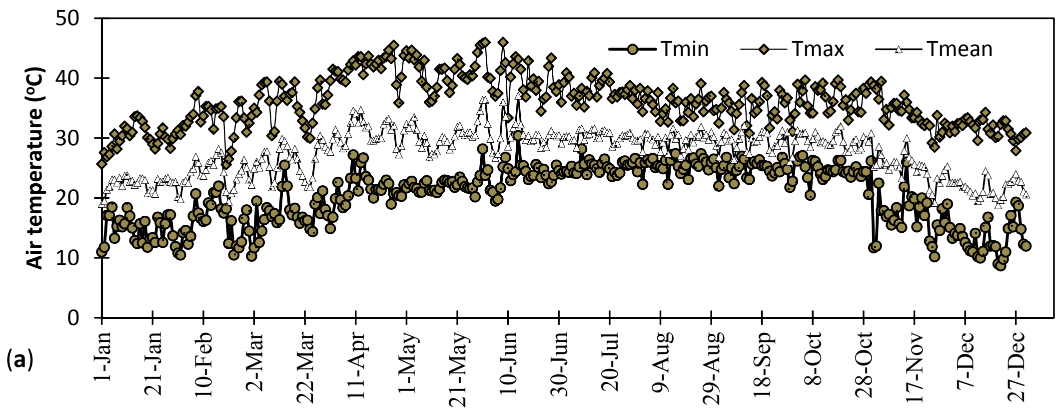


Figure 1. *Cont.*

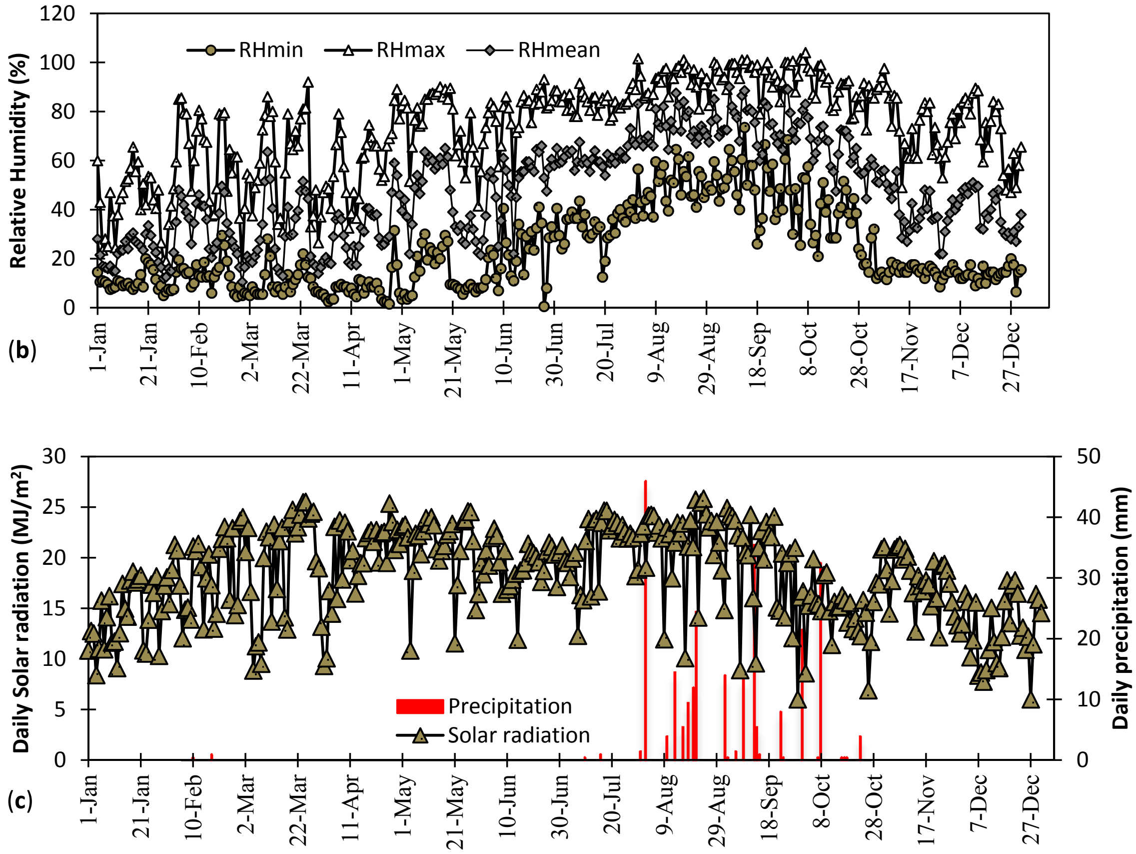
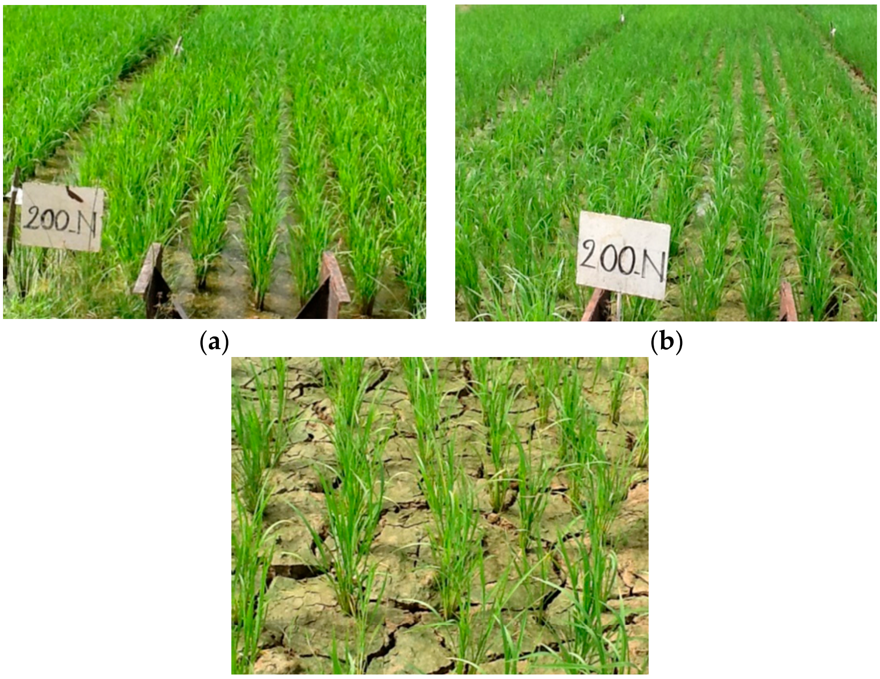


Figure 1. Variation of the (**a**) daily maximum, minimum and average temperature, (**b**) daily maximum, minimum and average relative humidity, and (**c**) daily solar radiation and precipitation from 1 January to 31 December 2015.

2.2. Experimental Design and Crop Management

Five rice genotypes were selected with similar cycle duration: NERICA S-21, NERICA S-44, Sahel 210, Sahel 202, and Hybrid AR032H. Rice cultivar NERICA S-21, NERICA S-44, Sahel 210, Sahel 202 are high-yielding varieties released in Senegal, and the Hybrid AR032H is a promising hybrid developed by AfricaRice, and which is a great candidate cultivar for release in Senegal. These cultivars were selected for their characterization in terms of optimum nitrogen fertilizer and irrigation water management. The regional nitrogen fertilizer recommendation is adopted and applied to a very large area in the Senegal River Basin regardless of soil types, soil residual nitrogen levels, and rice varieties [39]. It is, therefore, urgent to determine new nitrogen fertilizer recommendations for the newly developed rice genotypes in order to optimize nitrogen fertilizer and increase nitrogen use efficiency in the paddy field under sustainable agriculture. Under a constant dose of 50 kg ha^{-1} of phosphorus and 50 kg ha^{-1} potassium, five nitrogen doses—0, 50, 100, 150, 200 kg ha^{-1}—were investigated. The choice of these nitrogen doses was motivated by previous research results at the site and within the Senegal River Valley, showing unfilled grain at applied nitrogen doses of 100 and 150 kg/ha [3,4,10,39]. There is a need to apply higher nitrogen doses to improve grain filling when using high-yielding rice genotypes as NERICA S-21, NERICA S-44, Sahel 210, Sahel 202, and Hybrid AR032H.

Two alternate wetting and drying (AWD) irrigation regimes were used as a water saving strategy, compared with continuous flooding. A constant water layer of 5–10 cm depending on crop growth stage was maintained during the whole cropping season under the continuous flooding regime (Figure 2a). The first water saving regime considered was irrigating when the soil matric potential reached 30 kPa (AWD30) (Figure 2b), and in the second irrigation regime, crops were irrigated at 60 kPa matric potential level (AWD60) (Figure 2c). Watermark Granular Matrix sensors (WGMs, Irrometer, Co., Riverside, CA, USA) were used to monitor soil matric potential (SMP) on an hourly basis and averaged on a daily basis. WGMs are an indirect method of measuring SMP by directly measuring soil water tension. Two WGMs were installed in each plot at a depth of 15 cm to minimize variability in soil water content as consequence of land leveling. Under the continuous flooding irrigation treatment, irrigation was initiated each time the standing water reached 20 mm, with 30 mm of irrigation water being applied during the rice vegetative growth stage, and 80 mm of irrigation water during the rice reproductive phase. Under the AWD treatments (AWD30 and AWD60), 30 mm of irrigation water was applied at each irrigation event during rice vegetative stage and irrigation was similarly managed under AWD treatments as continuous flooding during rice reproductive phase to avoid/reduce sterility. Before imposing irrigation regimes on the treatments, 100 mm of irrigation water was applied for paddling and transplants survival. Therefore, 1140, 870 and 720 mm id irrigation water were applied to the CF, AWD30 and ADW60 plots, respectively, during the HDS with no rainfall. During the WS there was total of 149 mm of rainfall, and the total water supply was 889, 809 and 749 mm under the CF, AWD30 and ADW60 plots, respectively.



(**a**) (**b**)

(**c**)

Figure 2. Crop canopy and soil status under 200 kg N ha^{-1} under (**a**) continuous flooding, (**b**) AWD30, and (**c**) AWD60 during rice tillering stage.

The combinations of the three factors (rice cultivars, nitrogen fertilizer rates, irrigation regimes) were arranged under a split-split plot design with three replications. Irrigation regime, nitrogen rate, and the rice genotype were the main, subplot, and sub-subplot, respectively. The plot area was 5000 m^2, the subplots were 1625 m^2, and sub-subplots were 300 m^2. At a sub subplot, rice cultivars were randomly attributed to three replications. The three irrigation regime plots were separated by a 6 m buffer to avoid plot contamination by sub flow mostly from the continuous flooding plot. Urea (46% N), ammonium phosphate (18% N and 20% P), triple super phosphate (60% P), and potassium chloride (47% K) were used as sources of nitrogen, phosphorus, and potassium. Rice seedlings were transplanted at the rate of 25 hills m^{-2}. For all fertilizer treatments, 40% N, 100% P and 100% K were broadcast 21 days after transplanting. The remaining N dose was split-applied at panicle initiation

(40%) and 10 days before flowering (20%). Herbicide (propanyl, 6 L ha^{-1}) and manual weeding were practiced for weed control as needed. The herbicide was applied two weeks after transplanting, one day before the first N application; and thereafter, plots were kept weed-free by manual weeding. Insecticide (carbofuran (Furadan)) was sometimes used at 25 kg ha^{-1} for insect-pest and mite control at the start of tillering, maximum tillering, panicle initiation and flowering. At crop physiological maturity stage, rice was harvested, and grain yields were determined in each plot and adjusted to a standard moisture content of 14%.

2.3. Rice Accumulated Thermal Unit

Some of the rice variables were related to the thermal unit (TU), which is the accumulation of the growing degree days (GDD), which is cumulative temperature that contributes to plant growth during the growing season and is commonly expressed as:

$$TU = \sum_{i=1}^{n} \left(\frac{T_{\max} + T_{\min}}{2} - T_{\text{base}}\right) \quad (1)$$

where $T_{\max}$ = maximum air temperature, $T_{\min}$ = minimum air temperature, T_{base} = base temperature threshold for rice (10 °C), n is the number of days. The base temperature for calculating growing degree days is the minimum threshold temperature at which plant growth starts. The maximum and minimum average temperature thresholds of 35 °C and 10 °C, respectively, were used for rice growth in the Sahelian environment. All daily average temperature values exceeding the threshold were reduced to 35 °C, and values below 10 °C were taken as 10 °C, because no growth occurs above or below the threshold temperature values.

2.4. Estimation of Nitrogen Use Efficiency (NUE) and Partial Factor Productivity of Nitrogen (PFPN)

Nitrogen use efficiency (NUE) was estimated as grain yield advantage divided by the applied N rate [47–50]. NUE does not account for the contribution of indigenous N of the soil-floodwater system.

The partial factor productivity of Nitrogen (PFPN) quantifies total yield from nitrogen, relative to its utilization from all resources in the system, including indigenous soil nitrogen and nitrogen from applied inputs [51].

$$\text{NUE} = \frac{\text{YN} - \text{Yo}}{\text{Applied nitrogen rate}} \quad (2)$$

$$\text{PFPN} = \frac{\text{YN}}{\text{Applied nitrogen rate}} \quad (3)$$

where NUE and PFPN are in kg grain kg^{-1} N, YN is grain yield under N fertilizer and is in kg ha^{-1}, Yo is grain yield without N fertilizer and is in kg ha^{-1}, applied nitrogen rate in kg ha^{-1}.

2.5. Water Productivity (WP)

Rice water productivity was estimated as the ratio of grain yield to the total water supply. The total water supply is the seasonal irrigation amount in addition the effective seasonal rainfall amount.

2.6. Statistical Analysis

The analysis of variance (ANOVA) was performed to analyze the main effects of the three factors (irrigation regime, nitrogen rates, and genotypes) and their interactions using the statistical SAS software [52] and the means were cross-paired and compared using LSD at 5% of significance level.

3. Results and Discussion

3.1. Grain Yield and Optimum Nitrogen Fertilizer Rate

Factors of irrigation regime, nitrogen rates and genotypes ($p < 0.01$) and growing season significantly impacted grain yield ($p = 0.025$). The least significant difference ($LSD_{0.05}$) was 0.89 t/ha. Overall, grain yield showed quadratic relationships with nitrogen application rates under all three irrigation regimes. Under the conventional CF, all five genotypes achieved the highest yield at the nitrogen rate of 125 kg N ha^{-1} during the HDS, while yield increased with nitrogen rates up to 200 kg N ha^{-1} during the WS. During the HDS, rice genotype Sahel 210 had the highest yield of 11.10 t ha^{-1}, while NERICA S-44 showed the lowest yield at almost all applied N rates under CF. For the irrigation regime, NERICA S-21 exhibited the highest yield during the WS and NERICA S-44 consistently had the lowest paddy yield with nitrogen rates (Figure 3). However, paddy yields at 150 kg N ha^{-1} were statistically similar to the yield at 200 kg N ha^{-1}.

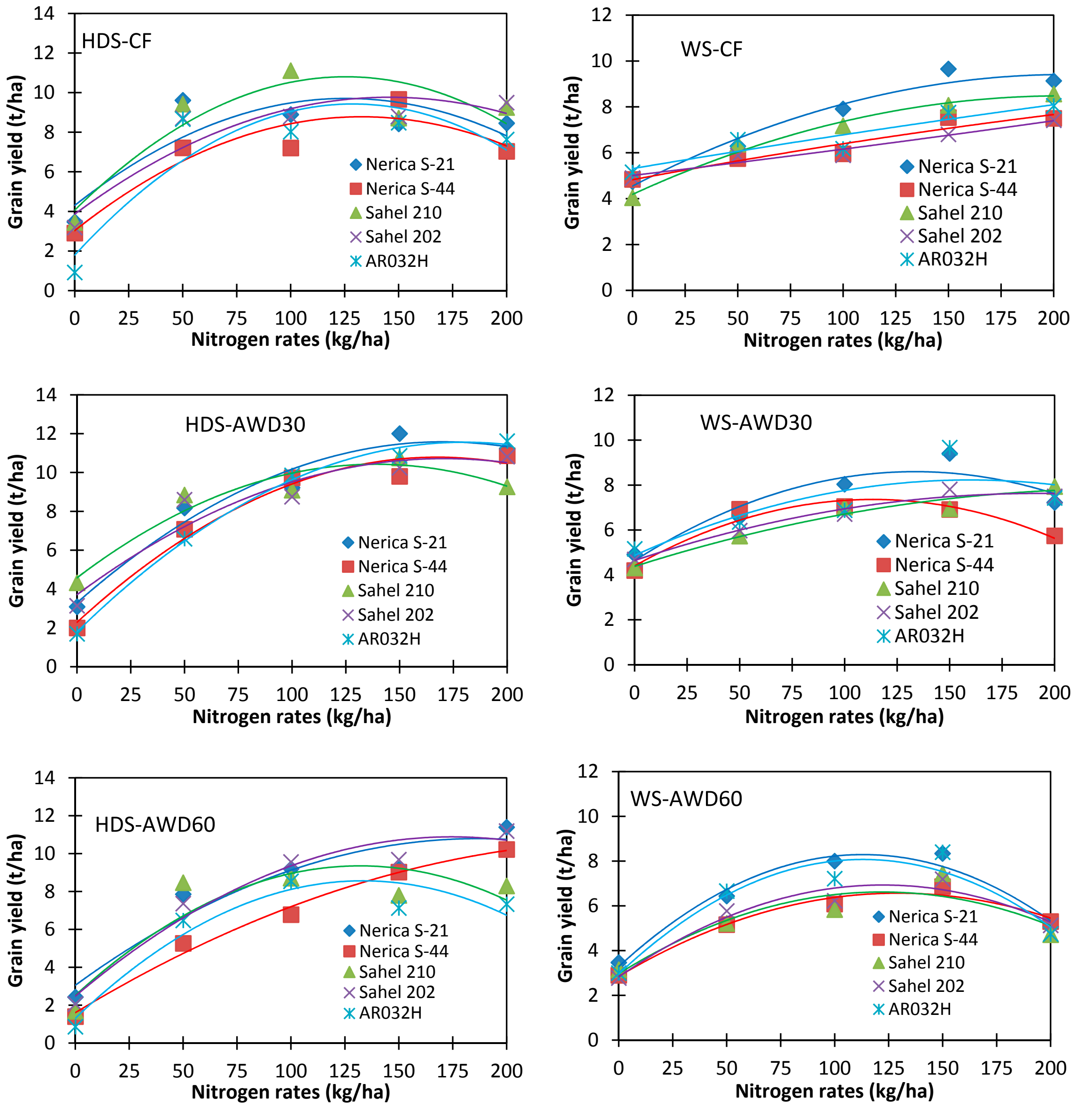


Figure 3. Relationships between the applied nitrogen rates and the paddy yield of five rice genotypes in the HDS and WS 2015.

Rice yield increased under AWD-30 compared to the CF treatment, and the maximum grain yields were obtained under 150 kg N ha^{-1}, with NERICA S-21 genotype showing the highest yield of 12.00 t ha^{-1} and the NERICA S-44 genotype showing the lowest yield of 10.24 t ha^{-1}. During the WS under the same irrigation regime, there were differences in the response of different genotypes to nitrogen rates. Rice genotype NERICA S-44 showed the maximum yield at 100 kg N ha^{-1} and the other genotypes still showed the maximum yield at 150 kg N ha^{-1} with the hybrid rice ARO32H and NERICA S-21 obtaining the highest yield of 9.70 and 9.41 t ha^{-1}, respectively (Figure 3).

Rice genotypes responded differently to water stress under the AWD-60 treatment during both HDS and WS. Sahel 202 and NERICA S-21 showed the best performance during both growing seasons, and the hybrid rice ARO32H and Sahel 210 obtained the lowest yield (Figure 3). Maximum grain yield was obtained at 200 kg N ha^{-1} for NERICA S-21, Sahel 202 and NERICA S-44 while the optimum nitrogen rate was 125 kg N ha^{-1} for Sahel 210 and ARO32H during the HDS. During the WS, all genotypes obtained the maximum yield under 120 kg N ha^{-1}, which was the recommended nitrogen rate within the study region, and yield thereafter decreased beyond 125 kg N ha^{-1} (Figure 3).

When all treatments were combined, rice average grain yield was 7.50, 8.3, and 7.11 t ha^{-1} for CF, AWD-30, and AWD-60, respectively, during the HDS; and 6.73, 6.69, and 5.65 t ha^{-1} for the respective irrigation regimes during the WS. Yield increase under AWD-30 during the HDS was 10.74% while yield decrease under AWD-60 was 5.14% during the HDS. The AWD-30 irrigation regime did not impact grain yield; however, the AWD-60 induced yield decrease of 16.09% as compared to the CF irrigation regime. The rice growing season has also affected grain yield with the HDS registering greater grain yield than the WS. Average rice grain yield during the WS accounted for 88.93, 80.60, and 79.50% of the HDS average grain yield under the CF, AWD-30, and AWD-60, respectively, while overall, the WS average yield was 83% of the HDS average yield. The greatest rice yield during the HDS could be explained by the greatest amount of solar radiation accumulated being 3261 MJ m^{-2} during the HDS compared to 2279 MJ m^{-2} during the WS, representing 70% of the solar radiation accumulated during the HDS (Figure 4a). Daily mean solar radiation was 21.6 MJ m^{-2} during the HDS and 18.5 MJ m^{-2} during the WS. Moreover, the accumulated thermal unit during the HDS was 2510.5 °C compared to 2269.2 °C during the WS (Figure 4b). In fact, during the HDS, there was clear sky with almost no clouds and only occasional rainfall, in contrast to the abundant cloud cover and more frequent rainfall events during the WS from August to late October, as shown in Figure 1, coinciding with the rice vegetative phase. However, the cumulative thermal unit as a function of days after planting is always higher during the WS after rice planting than during the HDS, implying greater crop growth rate during the WS with a shorter growing season of 123 days compared to 151 days for the HDS, as presented in Figure 4.

Rice paddy yield response to nitrogen rate exhibited a quadratic relationship during both growing seasons with coefficient of determination (R^2) varying from 0.70 to 0.92 (Figure 5). From the production functions, optimum nitrogen application rate was revealed to be 120 kg N ha^{-1}, 150 kg N ha^{-1}, and 150 kg N ha^{-1} under CF, AWD30, and AWD60, respectively, during the HDS, while during the WS, the highest yield was achieved by 150 kg N ha^{-1} under CF and 120 kg N ha^{-1} under the AWD irrigation treatments (Figure 5). Inter-seasonal and irrigation regime dependence differences in optimum nitrogen applied rate are translated into the differences in grain yield. Moreover, there were large discrepancies in the number of irrigation events among treatments. While there was non-significant effect of nitrogen application rate on the number of irrigations ($p > 0.05$), there were 28, 19, and 14 irrigation events under CF, AWD30, and AWD60 treatments, respectively, during the HDS, and 18, 14, and 11 irrigation events under the respective treatments during the WS. In other words, The AWD30 and AWD60 accounted for 70 and 59% of the CF irrigations during the HDS, and 75 and 62% of the CF irrigations during the WS. Barker et al. [53] and Richards and Sander [29] reported similar reductions in irrigation events under AWD when compared to CF irrigation.

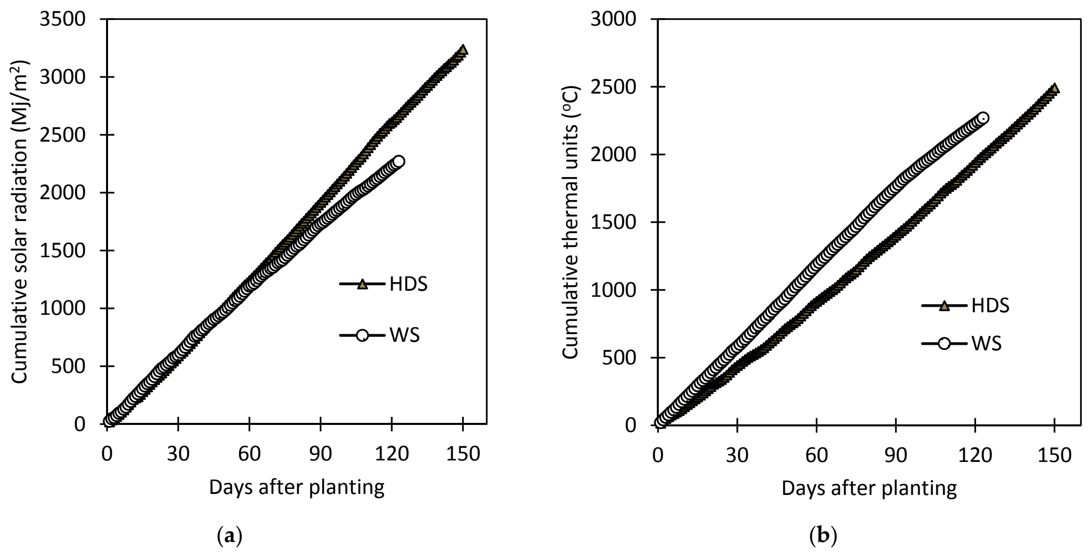
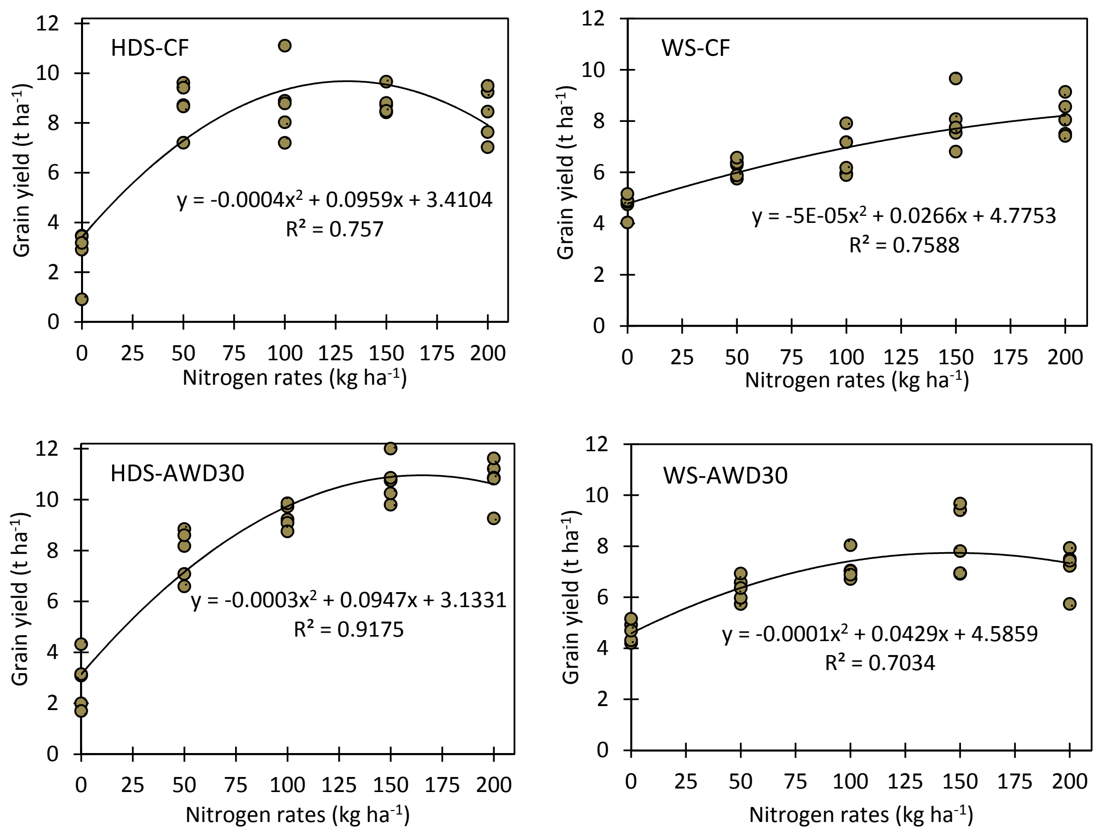


Figure 4. Cumulative solar radiation (**a**) and cumulative thermal units (**b**) in the hot and dry (HD) and wet (W) growing seasons as a function of days after planting.



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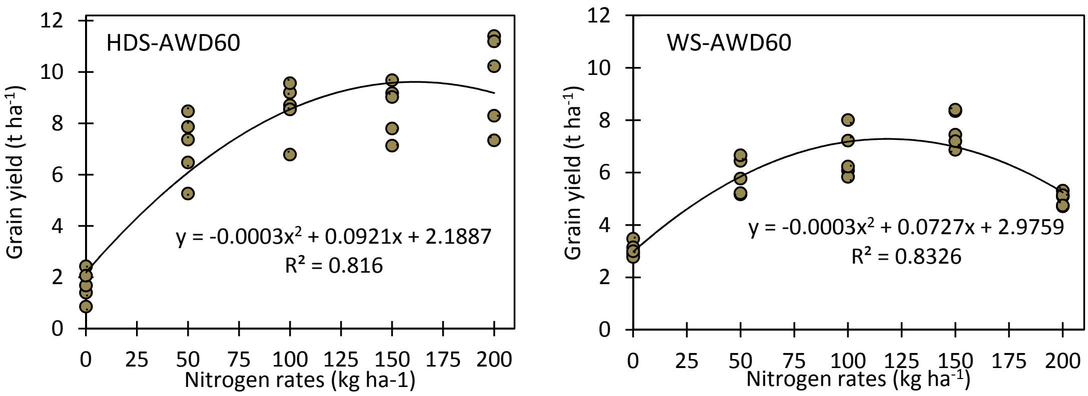

Figure 5. Rice yield-nitrogen production functions under different irrigation regimes and during the hot and dry season and the wet season.

This study showed the importance of adopting the irrigation water saving technology AWD-30, which achieved stability and even increase in grain yield, mostly during the HDS. The results of this study are not in agreement with Zhang et al. [54], who reported an increase in rice yield by 11% (when compared to the CF) when AWD was applied each time the soil matric potential reached 15 kPa at 15–20 cm and yield reduction by 32% under AWD applied each time soil matric potential reached 30 kPa at 15–20 cm in 2005 and 2006 in Yangzhou (China). They concluded that a moderate wetting and drying regime can enhance root growth, which benefits other physiological processes and results in higher grain yield and WUE. Matsuo and Mochizuki [55], from the evaluation of the genotypic differences in growth, grain yield, and water productivity of six rice cultivars under irrigation regimes from continuous flooding paddy (CF), alternate wetting and drying system (AWD), and aerobic rice systems in which irrigation water was applied when soil moisture tension at 15 cm depth reached 15 kPa and 30 kPa in A30, found specific responses of rice cultivars to irrigation regimes. They reported that the improved lowland cultivar, Nipponbare gave the highest yield in CF and AWD, while the upland cultivars UPLRi-7 and Sensho gave the highest yield in A15 and A30, respectively, and lower yields were achieved by the lowland cultivars. Koshihikari and Nipponbare under AWD15 and AWD30, respectively. The reported yields at AWD30 in this study are contrasting to the finding of Bouman and Tuong [56], who indicated that under AWD, yields usually declined when the soil matric potential during the non-submerged phase reached matric potential values of between 10 and 40 kPa.

The soil matric potential threshold for triggering the AWD irrigation might be dependent on soil type, management practices and other factors related to the local climatic conditions. Cababgon et al. [57] investigated AWD when the soil dried to a soil water potential at 15-cm depth of 10, 20, 50, and 80 kPa, and rice yield when AWD was applied at 10 kPa was similar to those of CF; yields of other AWD treatments were significantly lower than those of CF. They concluded that adopting AWD at 10 kPa combined with nitrogen rate of 180 kg N ha^{-1} will maintain high rice yield as for the CF, but the AWD at 20 kPa can be adopted when water and nitrogen fertilizer are scarce and costly. Optimal safe AWD irrigation regime is dependent on genotypes, management practices, nitrogen fertilization, agro-ecology and climate [54–56,58,59]. Bueno et al. [58] reported the critical threshold of soil water potential for AWD irrigation fixed at 30 kPa in heavy clay soil, varied among the 10 genotypes evaluated that showed different responses to AWD irrigation. de Vries et al. [3] reported a paddy yield range of 2.3–11.8 t ha^{-1} under WAD treatments and 3.7–11.7 t ha^{-1} under CF, and indicated that AWD irrigation regimes resulted in the highest yields in the WS in the Senegal River Valley and Delta, while during the HDS, the CF treatment out-yielded the AWD treatment, with the exception of AWD in the River valley. There is agreement between the results of this study and those reported by Ye et al. [59] and Liu et al. [58], who found grain yield similarly increased with reduced water input by AWD. Belder et al. [16] indicated rice yield maintenance at 70–80% of the CF in Asia when alternative irrigation methods were applied, with up to 50% of irrigation water being saved under sandy loam (Typic Haplustept) soil. Similar yield decline was shown in Asia under continuous aerobic rice cropping system [60]. The optimum N fertilizer rate of 120 kg N ha^{-1} shown under the CF during the HDS confirms the nitrogen rate recommended to maximize rice productivity [39]. Peng et al. [60] reported optimum nitrogen rates ranging 60–120 kg N ha^{-1}. In Louisiana, optimum nitrogen rates for the maximum rice yield were reported to be 157 and 151 kg N ha^{-1} under fall-stale seeded tillage and conventional tillage, respectively, [37], while the N fertilizer recommendation ranged from 134 to 179 kg N ha^{-1} [61]. The seasonal dependence of rice yield is similar to the reported results by Djaman et al. [10], and Bado et al. [62]. de Vries et al. [3] and Traore et al. [4] also reported higher yield during the HDS than the WS in the Senegal River Valley and Delta and the highest yield in HDS was attributed to better crop growth and development conditions during the HDS resulting in greater transpiration, greater spikelet production efficiency per unit biomass and greater biomass accumulation from flowering to physiological maturity [63]. Peng et al. [64] and Yang et al. [63] reported positive correlation between rice yield and the daily mean radiation during the growing period in the dry season. Furthermore, higher nitrogen fertilizer response by rice grown on the Andaqueptic Haplaquoll soil was observed during the dry season in the Philippines [65]. Stuerz et al. [66] reported highly significant correlations between meristem temperature at panicle initiation and spikelet fertility that could be a factor of yield decline in WS.

The quadratic production functions exhibited by rice yield in this study were also reported by Djaman et al. [39] for the aromatic rice varieties (Sahel 177, Sahel 328, Sahel 329, Pusa Basmati) in the same agro-ecological zone, with high R^2 as high as 0.99 at the same research station. Inter-seasonal variability observed in rice genotype yield response to nitrogen rate even in the same environment might be due to the influence of climatic factors and management practices on nitrogen-yield relationship. In addition, N recommendations should move from the regional level to site-specific management based on the residual soil nitrogen and rice yield target for sustainability of the cropping the system [39,67]. The results of this study are in agreement with Peng et al. [38], who reported curvilinear response of rice yield to nitrogen fertilizer applied rate. Linear response of rice to nitrogen rate below 150 kg N ha^{-1} and a plateau off when the applied N rate is greater than 150 kg N ha^{-1} was reported by Harell et al. [37]. Djaman et al. [68] found nitrogen uptake to be strongly related to watering regime on Hasting silt loam soil with field capacity of 34%, wilting point of 14% and saturation of 53%. Watkins et al. [69] reported four different yield response functions on potential N response functions (quadratic, quadratic-plateau, linear-plateau, and Mitscherlich) estimated depending on location and year.

3.2. Agronomic Nitrogen Use Efficiency (NUE)

Rice agronomic nitrogen use efficiency (NUE) was affected by water management and growing season, decreased with the nitrogen fertilizer rates and varied from 159 to 20.6 kg kg^{-1} N, from 109.2 to 24.7 kg kg^{-1} N, from 135.7 to 32.4 kg kg^{-1} N under CF, AWD30, and ADW60, respectively (Figure 6), and averaged 61.8, 64.3 and 65.6 kg kg^{-1} N for the respective irrigation regimes, respectively, during the HDS. Hybrid rice achieved the highest NUE under the CT and AWD30 treatments while the hybrid rice and Sahel 210 obtained the lowest NUE at the high nitrogen application rate under AWD60. There was an increase in NUE of 4 and 6% under AWD30 and AWD60, respectively, as compared to CF. As the production functions revealed the adoption of nitrogen fertilizer rate of 150 kg N ha^{-1}, the NUE under this particular nitrogen rate averaged 40.2, 52.5 and 41.8 kg kg^{-1} N, showing the profitability and the sustainability of rice production under the AWD30 irrigation regime. There is yield advantage of 12.3 kg of grain per unit (kg) of applied nitrogen, and the hybrid rice and the NERICA S-44 achieved the highest NUE at 150 kg N ha^{-1}. Rice NUE was lower during the WS and varied from 46.7 to 14.5 kg kg^{-1} N, 54.5 to 7.7 kg kg^{-1} N, and from 73.3 to 7.8 kg kg^{-1} N under CF, AWD30, and ADW60, respectively (Figure 6), and averaged 21.5, 23.5 and 33.1 kg kg^{-1} N, for the respective irrigation regimes. The hybrid rice and NERICA S-44 registered the lowest NUE under the CF treatment while Sahel 210 showed the poorest performance in terms of NUE under the AWD60.

At the optimum nitrogen rate of 150 kg N ha^{-1}, the hybrid rice achieved the highest NUE of 30.07 and 36.02 kg grain kg^{-1} N under AWD30 and AWD60, respectively, while Sahel 210 obtained the lowest NUE value of 17.6 under AWD30 and NERICA S-44 the lowest NUE value of 26.4 kg grain kg^{-1} N under the AWD60 irrigation regime. NERICA S-21 and Sahel 202 registered the highest and the lowest NUE values of 32.7 and 12.7 kg grain kg^{-1} N, respectively, under the CF treatment.

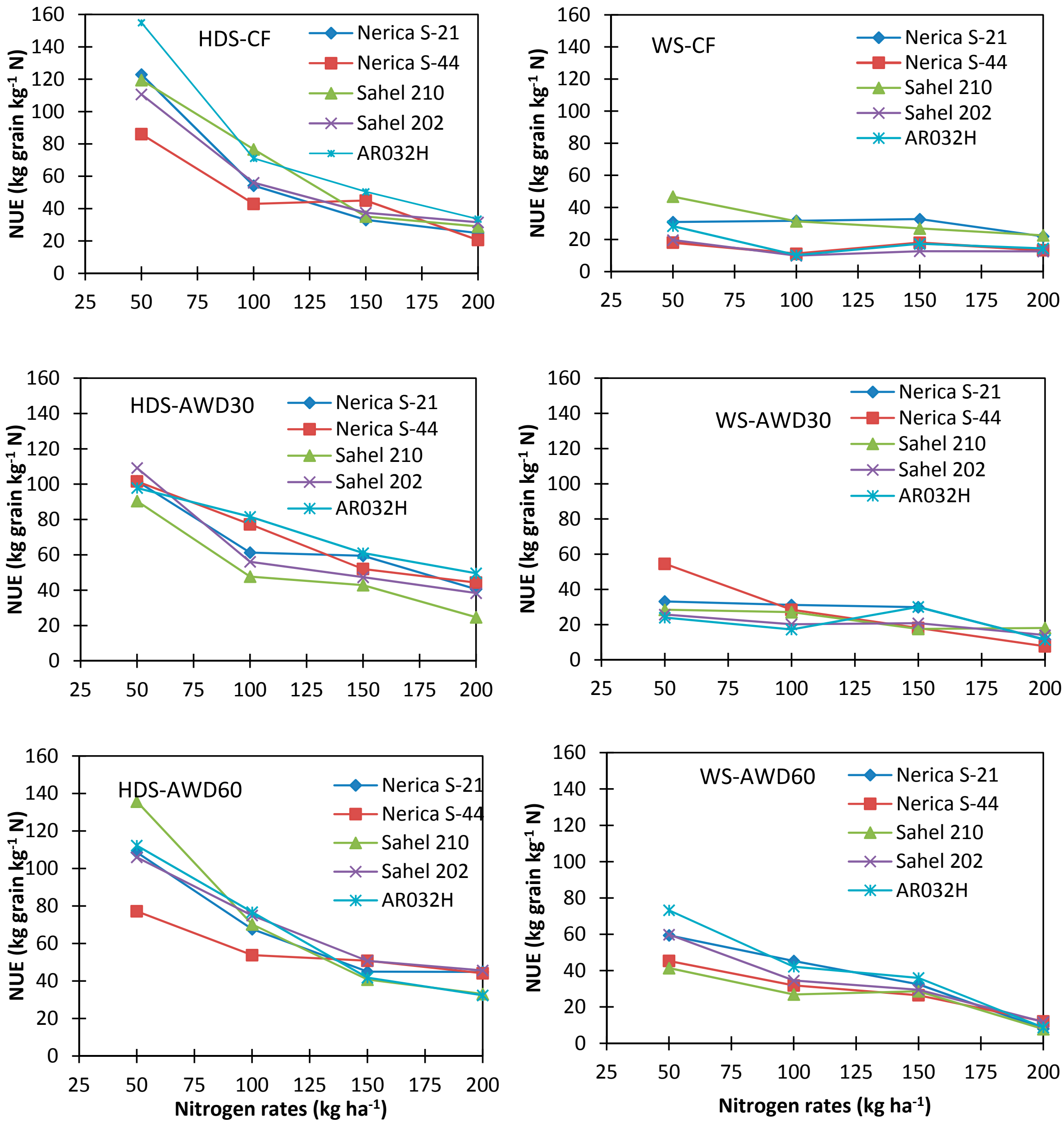

Figure 6. Variation in nitrogen use efficiency (NUE) of five rice genotypes as function of applied nitrogen fertilizer rates.

The results of this study are in agreement with Zhao et al. [23], who indicated that rice NUE was affected by the water management practices and NUE values varied from 2.0 to 17.9 kg grain kg N under system of rice intensification integrating AWD technology and 7.1 to 13.1 kg grain kg^{-1} N under traditional flooding. Cassman and Pingali [69] reported farmers' field NUE range of 15–20 kg kg^{-1} in the Philippines. Very low NUE value of 9.1 kg kg^{-1} N was reported by Peng et al. [70] in China while Wang et al. [71] reported NUE as low as 6.4 kg kg^{-1} N in farmers' fields. High nitrogen inputs 180–240 kg N ha^{-1} applied in farmers' practices might explain the low NUE of the nitrogen fertilizer [60]. Yang et al. [72] reported the greatest NUE to be obtained by the hybrid rice as compared to the inbred rice genotypes. Yang et al. [73] indicated that AWD irrigation regime is an important water management technology and an effective approach to improve the NUE of rice, which is influenced by many factors under AWD irrigation condition, including rice variety, ecological environment, nitrogen fertilizer management, and soil drying intensity. They pointed out that drying and re-watering cycle in AWD affects biochemical and physical processes namely nitrification, denitrification, mineralization, percolation, and leaching in soil by changing soil water and air equilibrium, which in turn affect the availability of nitrogen nutrition.

3.3. Partial Factor Productivity of Nitrogen (PFPN)

The partial factor productivity of nitrogen decreased with the nitrogen application rates and, similar to the NUE, it is dependent on rice growing season, irrigation regime, and the genotype. It decreased from 192.3 to 38.2 kg kg^{-1} N, from 176.8 to 40.3 kg kg^{-1} N, and from 196.3 to 36.7 kg kg^{-1} N under CF, AWD30, and AWD60 treatments, respectively, and averaged 90.8, 93.9 and 83.2 kg kg^{-1} N under the respective irrigation treatments, showing slight increase of rice PFPN under the AWD30 irrigation regime (Figure 7). At the nitrogen fertilizer rate of 150 kg N ha^{-1}, average rice PFPN was 58.8 kg kg^{-1} N under CF, 71.5 kg kg^{-1} N under AWD30, and 57.1 kg kg^{-1} N under AWD60. There is great increase in PFPN of 21.6% under AWD30 compared to the CF while it decreased about 2.9% under AWD60.

During the WS, PFPN of rice decreased from 131.5 to 40.2 kg kg^{-1} N from 138.6 to 28.8 kg kg^{-1} N, and 133.2 to 23.7 kg kg^{-1} N under CF, AWD30, and AWD60 treatments, respectively, and averaged 70.9, 72.0 and 64.9 kg kg^{-1} N under the respective irrigation treatments (Figure 7). NERICA S-21 achieved the highest PFPN under the CF while NERICA S-21 and the hybrid rice showed the highest values of the PFPN under both AWD30 and AWD60. The lowest PFPN values were obtained by Sahel 202 under the CF, Sahel 210 and NERICA S-44 under AWD30, and NERICA S-44 under AWD60. Considering the most promising nitrogen application rates of 120 and 150 kg N ha^{-1}, NERICA S-21 and the hybrid rice consistently achieved the greatest PFPN and might be adapted to AWD irrigation regime as reported by Sandhu et al. [74] found higher nodal roots, root length and higher root dry weight for four selected rice genotypes compared to IR64, which is a lowland-adapted variety. The improvement of this trait under AWD improves access to water and nutrient in the top soil layer and grain filling rates [75–77].

Thus, the AWD30 irrigation regime offers the opportunity to significantly improve rice PFPN during the HDW in the Senegal River Valley.

Zhu et al. [78] reported rice PFPN that ranged from 26.9 kg kg^{-1} to 69.1 kg kg^{-1} in Hubei Province (China) and Yang et al. [73] reported a range of 29.0–83.1 kg kg^{-1} with the highest PFPN achieved under moderate AWD treatment. Peng et al. [79] reported significant differences in PFPN among cultivars, ranging from 36.0 to 42.0 kg kg^{-1} in rice cultivars Huaiji, Binyang, and Haikou, was 58.2 kg kg^{-1} in Changsha, and 66.4 kg kg^{-1} in Xingyi. They reported about 9% higher average PFPN for the Hybrid rice than inbred cultivars. Dobermann [51] indicated that PFPN of irrigated rice could reach 60 kg kg^{-1} in well-managed systems or at low nitrogen applied rate. Peng et al. [79] reported variation in PFPN between sites and average PFPN was 39.4 kg kg^{-1} in Huaiji, Binyang, and Haikou, 52.5 kg kg^{-1} in Changsha, and 66.4 kg kg^{-1} in Xingyi. The results of this study are in agreement with Espiritu [80], who found variability in PFPN of the rice varieties with much larger range of 65.7–414.0 kg grain kg^{-1} N. Liu et al. [58] found that the site-specific nitrogen management combined with AWD irrigation regime increasing rice yield and PFPN as compared to the CF irrigation regime due to an increase in the number of spikelets per panicle, the percentage of filled grains, and grain weight under this treatment.

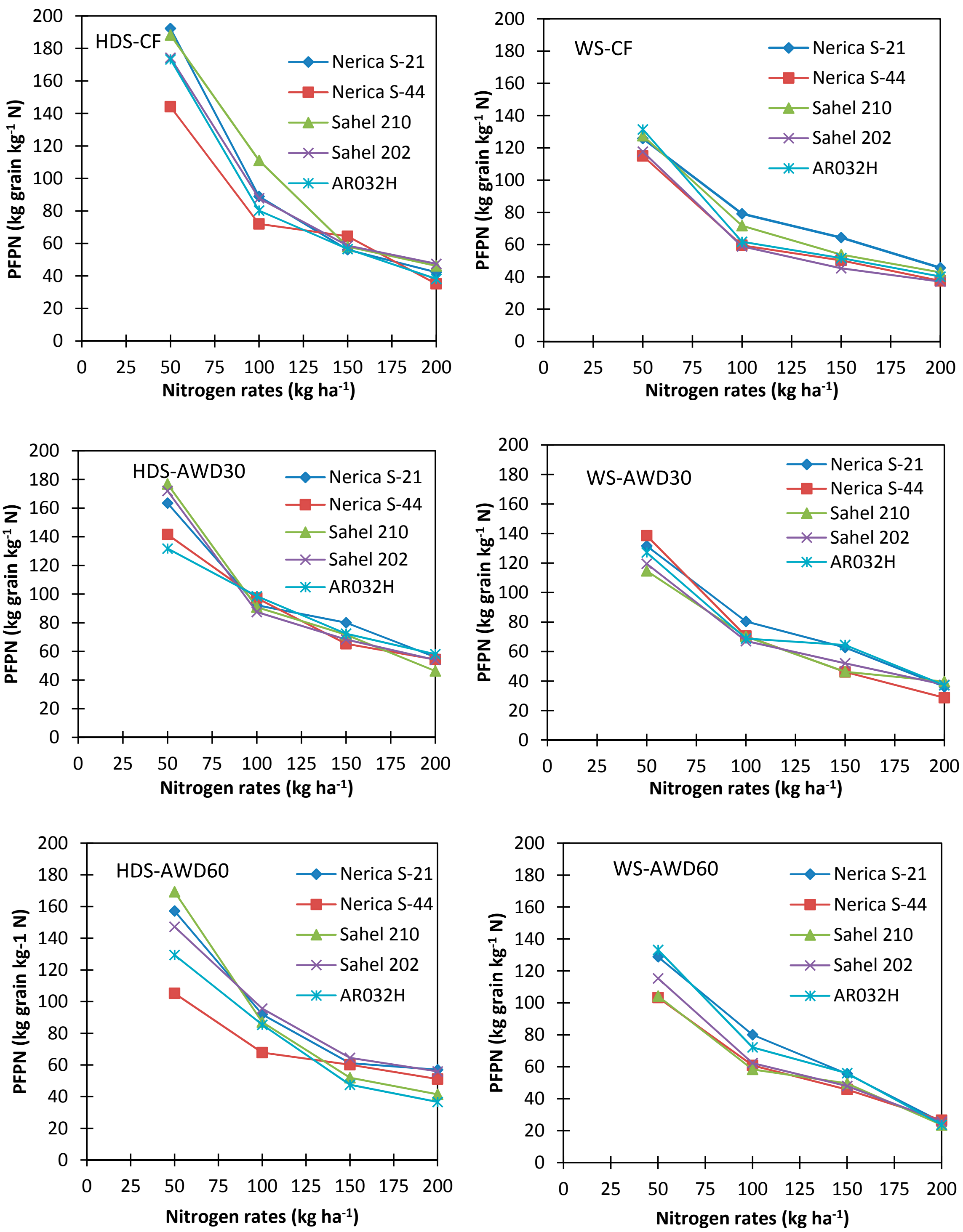

Figure 7. Variation in partial factor productivity of nitrogen (PFPN) of five rice genotypes as function of applied nitrogen fertilizer rates.

3.4. Water Productivity (WP)

Water productivity was estimated as the ratio of grain yield to total water supply. Overall, the lowest WP values under all watering regimes were obtained under zero nitrogen application, and WP increased with applied nitrogen rate during both HDS and WS. During the HDS under water saving regimes (AWD30 and AWD60), Nerica S21 achieved the highest WP (Figure 8). At the optimum nitrogen rate of 150 kg N/ha, Sahel 202 achieved the highest WP followed by Nerica S-21 while under

AWD30, the highest WP value of 1.3 kg/m^3 was obtained by Nerica S-21 under 150 and 200 kg N/ha. Under continuous flooding, the highest WP (0.97 kg/m^3) was obtained by Sahel 210 followed by Nerica S-21 and Sahel 202 (Figure 8). For all nitrogen rates combined, WP averaged 0.99, 0.95, and 0.66 kg/m^3 under AWD60, AWD30, and CF, respectively, during the HDS. During the WS, WP increased with nitrogen applied rate from 0 to 150 kg N/ha and decreased at 200 kg N/ha under AWD60, with the highest WP achieved by Nerica S-21 followed by hybrid rice ARO32H. Similar trend of WP was obtained under AWD30 with Nerica S-21 and ARO32H achieving the highest WP (Figure 8). Nerica S-21 also achieved the highest WP and Sahel 202 achieved the lowest WP under CF. Overall, WP averaged 0.75, 0.83, and 0.76 kg/m^3 under AWD60, AWD30, and CF, respectively, during the WS. Water saving strategies improve water productivity by 50% under AWD60 and 44% under ADW30 during HWS, while there was only 9% improvement in WP under AWD30 during the WS. The results of this study are in agreement with Ceesay [81] and Pascual and Wang [82] who reported increase in WP under intermittent irrigation while Carrijo et al. [83] reported a decrease in water productivity under AWD. While there is no agreement on improvement in water productivity under AWD, the implementation of AWD at field and scheme levels should consider soil type, local climate, season, and rice genotype.

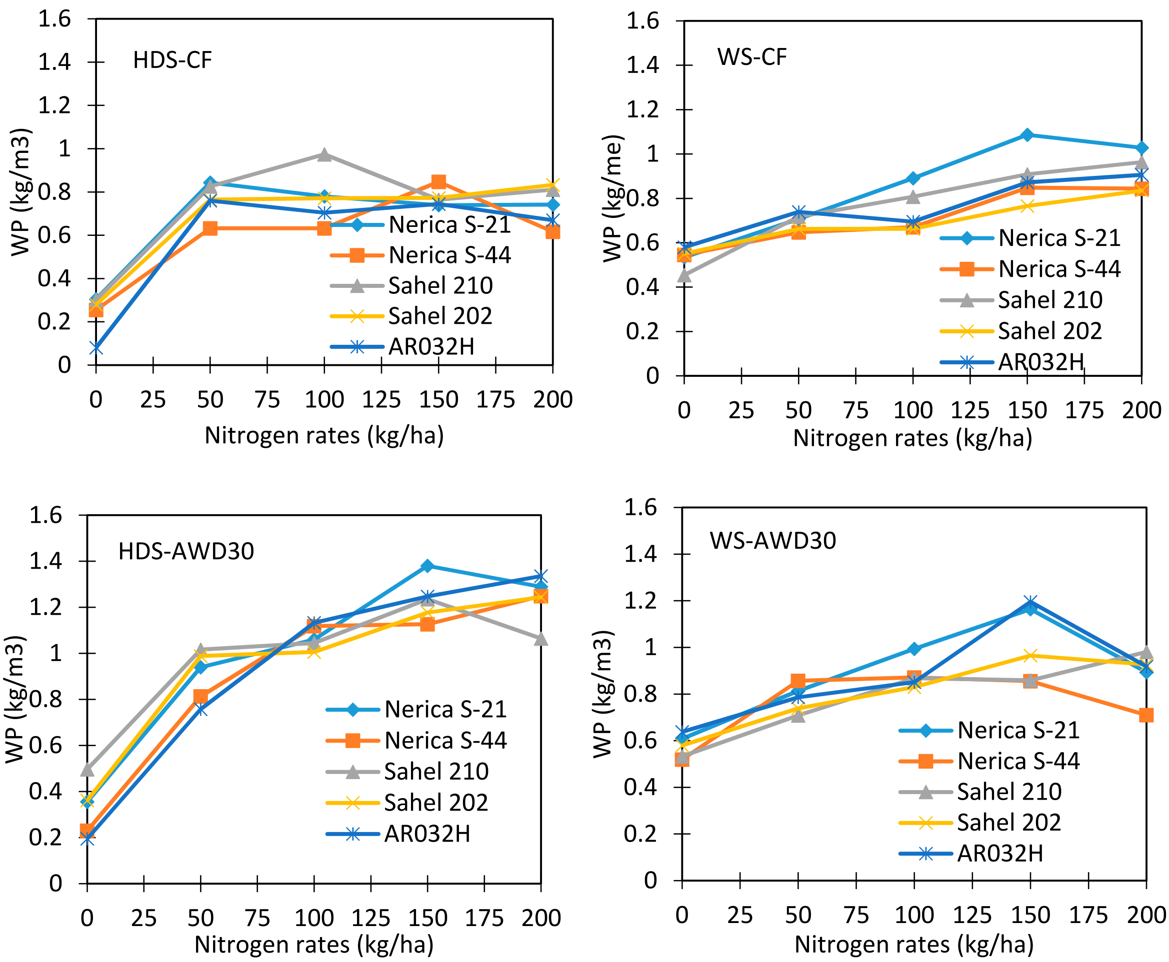

Figure 8. *Cont.*

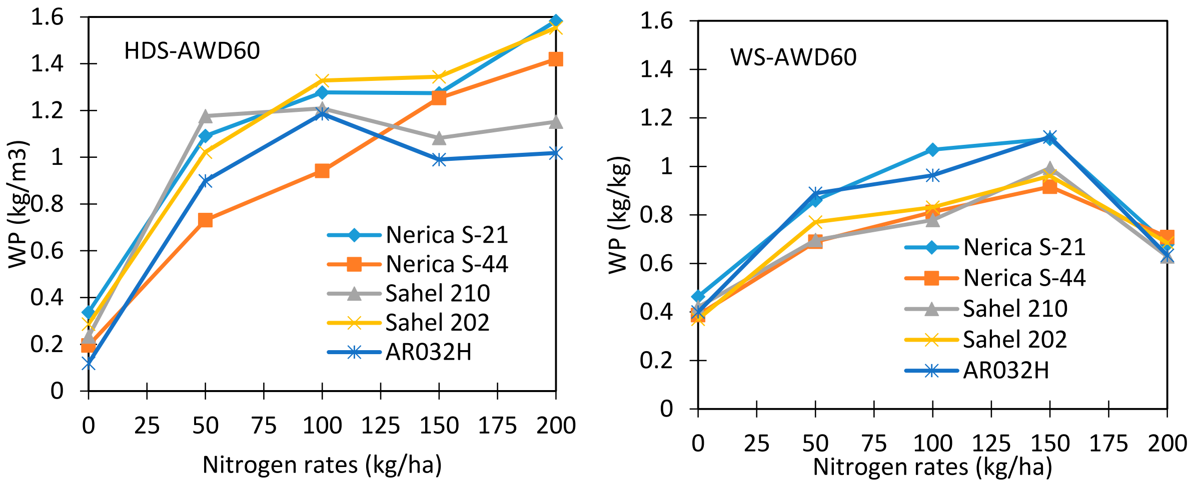

Figure 8. Variation in water productivity (WP) of five rice genotypes as function of applied nitrogen fertilizer rates.

4. Conclusions

Irrigation water saving strategies in rice production are becoming increasingly important to identify effective and sustainable crop production and management practices. In addition, these practices should be adopted in production agriculture. Thus, local data and information evaluating crop performance under different irrigation and nitrogen levels for different genotypes is critical for the success of this adoption. However, the technology practices are challenging due to differences in soil type, rice genotype, climate, management practices, and other factors. This study evaluated two alternate wetting and drying AWD irrigation regimes against the continuous flooding and the susceptibility of five rice genotypes under fine nitrogen fertilizer applied rates. Both irrigation regimes and nitrogen application rates affected rice yield and nitrogen use efficiency. Rice genotypes showed different response to the alternate wetting and drying irrigation with significant synergistic irrigation regime and nitrogen rates interaction. The AWD30 irrigation regime help achieving increase in rice yield of 18.2 and 6%, increase in nitrogen use efficiency of 30.6 and 8.4% during the two growing seasons under the optimum nitrogen applied rates, and reduction in irrigation events by 27.3% as compared to the continuous flooding irrigation regime. Therefore, AWD30 kPa is an effective AWD that can be adopted as water saving technology and for increasing production efficiency under paddy production in the Senegal River Middle Valley. Similar research should be conducted in the upper Valley, where soils are sandier, for the sustainability and the adoption of the irrigation water saving practices across the entire Senegal River Valley.

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