Co-fertilization of Silicon and Phosphorus influenced the Dry Matter Accumulation, Grain Yield, Nutrient Uptake, and Nutrient-Use Efficiencies of Aerobic Rice

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Abstract

Rice is known to be a nutrient exhaustive crop and the application of silicon (Si) has been reported for the better utilization of plant nutrients from the soil. Hence, the response of the plant to phosphorus (P) could be enhanced by co-fertilization of Si and P. The present study evaluates the dry matter production (DMP), grain yield, nutrients uptake, and nutrient-use efficiency (NUE) of Si and P application in aerobic rice (AR). Therefore, a field experiment was conducted at ICAR-Indian Agricultural Research Institute (ICAR-IARI), New Delhi, India in a factorial randomized block design (FRBD), the treatments comprised four levels of Si (0, 40, 80, and 120 kg Si ha^{-1}) and P (0, 30, 60, and 90 kg P_2O_5 ha^{-1}) application. The results revealed the significant effect of Si and P application on DMA, grain yield, and nutrient uptake in AR. The highest DMP and grain yield of AR was found with the combination of 120 kg Si and 90 kg P_2O_5 ha^{-1} closely followed by the combination of 80 kg Si and 60 kg P_2O_5 ha^{-1}. The rate of increase in DMP due to different doses of Si and P ranged between 7.6–25.6% over control. A strong positive relationship was observed between different doses of Si and P and concentrations and uptakes of different nutrients, barring zinc (Zn). Application of Si and P elevated the grain concentration of Si, nitrogen (N), P, and potassium (K) by 25, 16.5, 47, and 25%, respectively, over control. Overall, the addition of Si and P application in nutrient management could increase the productivity and NUE of AR.

Keywords Aerobic rice, Grain yield, Silicon, Phosphorus, Nutrient harvest index

1 Introduction

Rice (Oryza sativa L.) is a widely cultivated and a major staple food crop of Asia and Africa [1] and the global food security greatly depends on rice production [2]. Moreover, rice cultivation constitutes a source of livelihood for millions of people [3] in Asia and India as well. The burgeoning population of India would require 380 million tons (mt) of food grains by 2025. To ensure the food security of the country without deteriorating the soil health and environment has become the major challenge to the researchers, farmers, and policymakers. In this regard, growing rice in aerobic situation could be a solution. Aerobic rice (AR) is a different technique of rice cultivationv, where rice is grown on well-drained, non-puddled, and non-saturated soils without flooding the soil [4]. Therefore, balanced nutrition is essentially important to increase the productivity of AR as cultivating rice under aerobic conditions makes the crop more nutrient-exhaustive [5]. The amount of Si in the earth's crust is about 29% [6]. Despite its plethora of amount in the soils, Si has not yet been recognized as an 'essential' nutrient for the cultivated crops [7], because of its very minor role. However, in present-time, Si is being considered as a beneficial nutrient, particularly for rice, Si plays a vital role in crop growth and development [8].

The rice plant accumulates a large amount of Si [9]. Plants absorb Si in the form of soluble monosilicic acid, which plays an imperative role in biotic and abiotic stress resistance in plants [10–12]. The soil application of Si is one of best management practices (BMPs) being followed by many farmers across the world for the sustainable production of rice, wheat, sugarcane etc. [13]. Savant et al. [14] showed that Si uptake in rice is greater than the uptake of N and K in the above ground biomass. Similarly, phosphorus-use efficiency (PUE) increased from 24–34% when P was added along with the Si, this is mainly owing to reduced

P retention capacity and increased availability of water-soluble P in soil [15]. Many studies have demonstrated the positive yield response of crops to Si application [16]. Due to the complementary effect, Si application has the potential to increase NUE, leading to enhanced rice productivity. Haldar and Mandal [17] reported that a significant increase in rice dry matter accumulation (DMA) due to the application of P. Similarly, Si application in rice, not only improved the translocation of the nutrient in the plant system but also water productivity by minimizing the transpiration losses [18]. Si fertilization improves the stiffness of the cell wall by increasing the accumulation of Si-bond of organic compound beneath the cuticle of the plant [19]. This helps in boosting the leaf architecture and photosynthetic efficiency [20]. Co-application of N and Si has been resulted in greater uptake of N and Si in the above ground biomass, and greater nitrate reductase activity and DMA [21]. Similarly, soil application Si along with K significantly improved the photosynthesis, grain yield and yield attributes of wheat plant [22].

In rice soils, co-fertilization of Si and P may overcome the deficiency of P by improving P uptake [23], and further enhances available Si in the soil and improve crop productivity [24]. Si application may enhance the availability of P in the soil by improving the competition between silicate and phosphate for sorption on Al and Fe oxide surfaces which have positive charges [25]. Co-fertilization of Si and P may thus substantially improve the Si and P bio-cycling with in the soil and plant. On the other hand, paddy-growing zones of India are converting into Si deficient zones due to intensive paddy cultivation and excluding the application of Si fertilizers. [14]. A very few studies have been done to evaluate the co-fertilization of Si and P on DMA, grain yield, and nutrient uptake in AR. Therefore, we hypothesized that the application of P and Si will have a positive role in enhancing the NUE of applied nutrients, crop yield, and DMA of AR. The objective of the study was to know the effect of Si and P co-fertilization in improving crop yield and DMA of

AR and to assess the effect of Si and P on the concentration and uptake of Si and other macro and micronutrients.

2 Materials and Methods

2.1 Experimental Location

This experiment was conducted during *kharif* (rainy) season of 2015-2016 at ICAR-Indian Agricultural Research Institute, New Delhi. Table 1 represents the detailed information about the physio-chemical parameters of the experimental soil. The study area has a sub-tropical and semi-arid type climate with hot-dry summer, cold winter and constitutes a part of 'Trans-Gangetic plains' agro-climatic zone. January-February, May–June and July-August are the coolest, hottest and wettest months of the year, respectively. The maximum and minimum temperature goes between 41–46°C and 5–7°C. The average annual rainfall (RF) is about 650 mm. The annual mean pan evaporation is about 850 mm. The weather data (temperatures, relative humidity, RF, and sunshine hours) of the experimental site during the have been depicted in Figures 1 and 2.

2.2 Experimental Treatments and Design

The investigation was conducted in a Factorial-RBD with three replications. Four levels of Si application (0, 40, 80, and 120 kg ha^{-1}) and four P application levels (0, 30, 60, and 90 kg P_2O_5 ha^{-1}) were taken as treatment. The dimension of the unit plot was 2.5 × 4.0 m (12 m^2). For the application of Si and P, calcium silicate (CS) and di-ammonium phosphate (DAP) were used, respectively. The nutrient content of the CS and DAP was 24% Si and 46% P_2O_5, respectively. CS was first mixed properly with the sand and then applied as a basal application in the soil before sowing. Similarly, P was applied as a basal application before the sowing of AR. The rice variety Pusa 612 was used as planting material for the study.

2.3 Land Preparation and Crop Management

Pre-sowing irrigation was applied to the field before sowing of AR to obtain optimum tilth and later to ensure good germination. First, the field was ploughed with tractor-drawn disc plough followed by harrowing using a rotavator and finally leveling with laser land leveler to obtain fine tilth. The treatment plots were demarcated according to the layout plan. Irrigation channels were formed using a bund maker. Dry seeding through seed drill was done in rows 20 cm apart. The seeds were sown at 5 cm depth at a seed rate of 40 kg ha^{-1}. The weeds were controlled by applying Pendimethalin @ 1 kg ha^{-1} immediately 1 day after sowing (DAS) of the crop, followed by two-hand weeding at 20 and 40 DAS. The recommended dose of nitrogen (120 kg N ha^{-1}) and potassium (60 kg K_2O ha^{-1}) were also applied to the crop through urea and potassium chloride, respectively. N was applied in 3 split doses. Irrigations were applied from soil dryness to the hair crack formation stage.

2.4 Dry Matter Accumulation and Grain yield

Five plants were randomly selected and collected by cutting from the ground level in each treatment at different stages of growth. These samples were shade dried for 5–7 days and then oven-dried at 70°C for 24 hours. Total DMA was expressed in g m^{-2} at 30, 60, 90, and at harvest. Rice grain yield was measured by harvesting and threshing crop plot-wise. Final grain yields have been reported at 14% moisture content.

2.5 Plant Analysis, Nutrient Concentration, and Uptake

Plant samples, both grain, and straw were collected during harvest, dried in a hot-air oven at 70°C for 24 hours, and smashed to pass through a 40 mesh sieve in a Macro-Wiley Mill. For each plot, 0.5 g of finally prepared grain and straw samples were taken for nutrient analysis. The N, P and K concentrations in grain and straw were determined by the modified

Kjeldahl method, vanado molybdophosphoric acid yellow color method, and flame photometer, respectively [26]. The concentration of iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) in the digested plant samples were determined using an atomic absorption spectrophotometer [27]. Silicon concentration was determined by autoclave induced digestion method [28]. The nutrient uptake in grain or straw was calculated by multiplying their respective nutrient concentrations with the corresponding yield. The total uptakes of nutrients were determined by adding up their respective uptake in grain and straw.

2.5.1 Nutrient harvest index

Total nutrient uptake was calculated by adding the nutrient uptake by grain and straw. Nutrient harvest index (NHI) of different nutrients was computed using the following as outlined by Dass et al. [29]:

$$\text{NHI (\%)} = \frac{\text{Uptake of particular nutrient by grain (kg ha}^{-1}\text{)}}{\text{Total uptake of that nutrient in biomass (kg ha}^{-1}\text{)}}$$

2.6 Nutrient-use efficiency

The estimated values of partial factor productivity (PFP), agronomic efficiency (AE), and physiological efficiency (PE) of applied Si/P were computed using the following equation as suggested by [30–31]:

Partial factor productivity

It is calculated by using the following formula:

$$\text{PFP} = \frac{Y_k}{SP_a}$$

Wherein, Y_k– Yield (kg ha^{-1}) and SP_a refers to the amount of Si/P applied (kg ha^{-1})

Agronomic efficiency (AE) of applied Si and P

It is calculated by using the following formula:

$$\mathrm{AE} = \frac{\text{Grain yield in treated plot (kg ha}^{-1}) - \text{Grain yield in control plot (kg ha}^{-1})}{\text{Amount of Si/P applied (kg ha}^{-1})}$$

Physiological efficiency (PE) of applied Si and P

It is calculated by using the following formula:

$$\mathrm{PE} = \frac{\text{Grain yield in treated plot (kg ha}^{-1}) - \text{Grain yield in control plot (kg ha}^{-1})}{\text{Si/P uptake in treated plot (kg ha}^{-1}) - \text{Si/P uptake in control plot (kg ha}^{-1})}$$

2.7 Statistical Analysis

The data recorded from the investigation were analyzed statistically using the F-test. The significant differences between treatments were compared by critical difference at a 5% level of probability using the F-test [32]. After that, pooled analysis of the data was performed following the standard norms of the ANOVA. The Pearson correlation analysis and principal component analysis (PCA) were accomplished using R software (R version 3.5.1) to depict the correlation among the various parameters and their relationship with the different treatments. A simple linear regression was performed to show the relationship between the different parameters and Si application.

3 Results and Discussion

3.1 Dry Matter Accumulation

The DMA varies significantly due to the application of Si and P at 60, 90 DAS, and harvest (Table 2). A significantly higher DMA was recorded with the treatment receiving 90 kg P_2O_5 ha^{-1}. However, this treatment was found on par with 60 kg P_2O_5 ha^{-1} in the pooled analysis. This might be due to adequate availability of P which leads to vigorous and taller plants with larger leaf areas, facilitating higher photosynthates production, finally resulting in enhanced DMA [33]. Jain and Dhama [34] reported that application of P up to 90 kg P_2O_5 ha^{-1} significantly increased DMA by 5–10% over control and 30 kg P_2O_5 ha^{-1}, respectively. These results confirm the findings of Singh et al. [35]. Among the Si application, DMA at (60, 90 DAS, and at harvest) was higher with 120 kg Si ha–1 which was on par with 80 kg Si ha^{-1} in the pooled analysis. The higher DMA could be due to the reason that Si fertilization enhances photosynthetic rate leading to increased DMA. Gerami et al. [36] reported that with the increase of Si levels, the leaf area of the plant increased, which enhanced photosynthetic rate and prevented the destruction of chlorophyll, and finally increased DMA of rice. Silicon-induced erectness of leaves results in increased photosynthesis improves water usage and decreases transpiration which eventually accumulates more dry matter [37]. This increase in DMA might be due to an enhanced P availability in the soil, led to better root growth and uptake of P in the above ground biomass through Si application [38–39].

3.2 Grain yield

The grain yield was influenced significantly by the P application (Table 2). A significantly higher grain yield was recorded with 90 kg P_2O_5 ha^{-1} than other levels of the P. However, it was statistically similar with 60 kg P_2O_5 ha^{-1}. There was 32% increment in grain yield by 90 kg P_2O_5 ha^{-1} over control. The increase in grain yield was possibly due to better growth, more fertile tillers, and grains and test weight [33]. The economic yield of rice is determined by tillering potential, which have close linkage with number of panicle and eventually grain yield [40]. Similar results were obtained by [41]. The Si fertilization also influenced the grain yield significantly. A strong positive linear relationship was observed between grain yield and Si application (R2 =0.8068, $P < 0.05$, Fig 3). The higher grain yield was recorded in the treatment receiving 120 kg Si ha^{-1} than rest of the Si treatment. There was 39% increment in grain yield by 120 kg Si ha^{-1} over control. Pati et al. [3] has also reported a significant increase in grain yield with increasing levels of Si. Adequate Si application might have increased the photosynthetic activity that enabled AR to rack up adequate photosynthates with higher DMA and efficient translocation led to more panicles with a higher test weight of filled grains, eventually led to higher grain yield [10, 18].

3.3 N concentration and uptake

Different doses of Si and P application had exerted a significant influence on N concentration and uptake both by grain and straw. The different levels of P and Si in-creased the N concentration in grain and straw by 16.5 and 29%, respectively (Table 3). A strong positive linear relationship was observed between Si and N uptake (R2 =0.807, $P < 0.05$, Fig 4). The uptake of N exhibited an increase when the P dose was raised from 30 to 60 kg P_2O_5 ha^{-1}. Maximum uptake of N recorded in the treatment receiving 60 kg P_2O_5 ha^{-1} than other levels of P (Table 4). P fertilization led to an increase in root growth which finally proved effective in increasing the N uptake. Improved P nutrition led to an increase in N content in the grains and straw because it helped in N acquisition by plants and their retention in economic parts of rice plant [42]. Among Si levels, the highest N uptake was recorded in the treatment receiving 80 kg Si ha^{-1} found on par with 120 kg Si ha^{-1} in the pooled analysis. This might be due to higher availability in soil-available N and N-use efficiency by the application of Si, which increased with increasing levels of Si [15].

3.4 P concentration and uptake

The different levels of P and Si increased the P concentration in grain and straw by 47 and 33%, respectively (Table 3). A strong positive linear relationship was observed between Si and P uptake (R2 =0.8797, $P < 0.05$, Fig 5). The maximum P uptake in grain (18.4 kg ha^{-1}) and straw (8.24 kg ha^{-1}) were recorded with 90 kg P_2O_5 ha^{-1}, it was at par with 60 kg P_2O_5 ha^{-1} (Table 4). This might be due to more solubility of P in soil and balanced supply of P due to increased levels of P, which resulted in improved availability and uptake by crop in respective treatment. These results are in close conformity with the findings of [43]. Among the Si application maximum, P uptake in grain (17.9 kg ha^{-1}) and straw (8.17 kg ha^{-1}) were obtained with 120 kg Si ha^{-1} however, it was at par with 80 kg Si ha^{-1} in the pooled analysis. Uptake of P increased with the application of Si in soil [44]. The optimum supply of Si might have increased P availability and solubility by reducing the retention capability of P in the soil which led to higher root growth and PUE [3].

3.5 K concentration and uptake

The different levels of P and Si increased the K concentration in grain and straw by 25 and 23%, respectively (Table 3). The maximum K uptake in grain and straw was obtained with 90 kg P_2O_5 ha^{-1} (Table 4). However, this treatment was found at par with 60 kg P_2O_5 ha^{-1}. Zhang et al. [45] also reported that the concentration and uptake of P in different plant organs increased with increasing its applied rate in the soil. It may be due to the desorption of P from adsorption sites within the soil. The productive response of Si application in relation to K uptake was detected at 120 kg Si ha^{-1}. A strong positive linear relationship was found between Si and K uptake (R^2 =0.8588, $P < 0.05$, Fig 6). This could be associated with the silicification of the cell wall [3]. The enhancement in uptake was mainly because of the increased concentration of K in the sink as well as increased yield. Chanchareonsook et al. [46] reported that balanced application of NPK fertilizers and Si significantly improves total N, P, and K uptake in rice. Singh et al. [15] observed that the Si fertilization in rice improved the K uptake significantly. Tahir et al. [47] reported increased uptake of K with the application of Si under saline conditions and thus enhancing dry matter and crop yield. Increased K uptake and decreased Na uptake by addition of Si could be the major tolerance mechanisms responsible for better growth of plants under salinity. Further, Si fertilization could attenuate the K-deficiency by maintaining plant turgidity, stomatal conductance and rate of transpiration [48].

3.6 Si concentration and uptake

The different levels of P and Si increased the Si concentration in grain and straw by 25 and 64%, respectively (Table 3). Among P application maximum value of Si uptake in grain and straw was obtained with 90 kg P_2O_5 ha^{-1}, which was found at par with 60 kg P_2O_5 ha^{-1} (Table 4). Increased application of P in rice is having a beneficial effect in enhancing Si content in stem sheath and also increases water-soluble Si in soil [18]. So, the balanced application of P to rice is very much essential to improve the Si uptake and this, in turn, avoids the crop lodging and increases pest and disease tolerance and other abiotic stress in rice plants. Among the Si applications, the highest Si uptake in grain (87.2 kg ha^{-1}) and straw (338.2 kg ha^{-1}) was recorded with 120 kg Si ha^{-1}. There was a strong positive linear relationship between the amount of Si applied and Si uptake in above-ground biomass ($P<0.05$, $R^2 = 0.9145$, Fig 7). However, this treatment was found at par with 80 kg Si ha–1. This increased Si uptake might be linked with increased Si supply, which increased the Si availability to root system, which enabled the rice plant to absorb more Si from soils. Jawahar et al. [49] also reported that despite its ubiquity in soil, soil solution has very minute quantity of available-Si and its uptake is largely linked with Si-supplying capacity of the soil. Increased soil phosphatase activity with the application of Si fertilizer was also observed by [50]. Rice have potential to absorb Si by active as well as passive process, However, decrease in temperature or physiological inhibitors may affect its uptake [51].

3.7 Nutrient harvest index (NHI)

Results indicated that P application affected NHI of P and Si significantly (Table 3). P application treatments were significantly ineffective to influence NHI of N and K in the pooled analysis. NHI values followed the order of N>P>Si>K. In the case of Si application, NHI did not differ significantly among Si levels. However, the highest values of NHI were recorded with 120 kg Si ha^{-1} except for NHI of K and Si, where they were higher with 80 kg Si ha^{-1}. NHI values are an indicator of relative partitioning of nutrient to grain, represented as the ratio of grain nutrient removal to total nutrient accumulation [52]. The Higher N harvest index over the other nutrients in AR was due to the higher respective nutrient uptake [53]. This could also be due to the higher relative uptake of nutrients in grain relative to their total uptake [54]. Principles of the law of diminishing returns could better explain the general trend of NHI in crops [55].

3.8 Zn, Fe, Mn, and Cu uptake

Zinc uptake in grain and straw of rice were influenced significantly by Si and P levels (Table 5). The uptake of Zn decreased with increasing doses of P applications. The lowest Zn uptake in grain and straw was recoded with the highest dose of 90 kg P_2O_5 ha^{-1}. Rehim at al. [56] also reported that the P fertilization (40 to 120 kg ha^{-1}) to rice drastically reduced the Zn concentration and uptake. Therefore, the higher dose of P reduced the availability of Zn in the plant. Similarly, Zhu et al. [57] reported that concentration of Zn in plant reduced with increasing the dose of P application. It has already been observed that application of P at higher dose causes Zn deficiency in crop plants. Ryan et al. [58] reported that application of P fertilizers at higher dose results in Zn deficiency in plants owing to the dilution effect. The uptake of Zn also fell with increasing doses of Si applications. The lowest uptake of Zn was recorded with the highest dose of 120 kg Si $ha^{-1.}$ Soil application of Si resulted in a reduction of Zn content by 41–56% in shoots, 21–41% in roots of rice [59]. Several authors observed that the application of Si as silicates to the soil can lead to the immobilization and decreased availability of metals for crop plants. Bokor et al. [60] reported on precipitation of insoluble Zn_2SiO_4 under the application of Si. [61–64] reported that Si reduces the translocation of heavy metals from the roots to above ground parts of the plant. They reported that there was a heavy accumulation of Si in the root endoderm of rice plants, which acted as a barrier, which reduced the permeability of the cell walls of the inner roots tissues, thus blocking of translocation of heavy metals the apoplast.

The P application showed a significant effect on Fe, Mn, and Cu uptake in rice grain and straw (Table 5). The maximum value of Fe, Mn, and Cu uptake in grain and straw was observed in the treatment receiving 90 kg P_2O_5 ha^{-1}. However, this treatment was statistically similar with the treatment receiving 60 kg P_2O_5 ha^{-1}. Ali et al. [65] reported that P application improved the concentration of Fe and Mn, probably owing to the complementary interactions between applied P and these two micronutrients in the soil. Furthermore, the applied P increases the extractable Fe and Mn reduces the soil pH, enabled these metals to be more soluble in the soil led to more uptakes by the plant. However, the same group of scientists reported decreased concentration and uptake of Cu with increasing dose of P. The reduced availability due to interference of applied P is very common in soils. It might be due to the genesis of insoluble forms of Cu, such as Cu-phosphate. Paramesh et al. [66] reported application of P through chemical fertilizer or compost significantly increased the Fe concentration and uptake in wheat [66]. Among the Si applications, the highest Fe and Mn uptake in grain and straw was recorded with 120 kg Si ha^{-1}. However, this treatment was at par with 80 kg Si ha^{-1}. Swain and Rout [67] studied the interaction of Si with micro-nutrient. The result showed that Si accumulation was an optimum and positive association with Fe, Mn, and Cu by encouraging their utilization. Rice plant showed enhanced utilization of Fe, Mn, and Cu with increasing Si levels. Overall Mn, Fe, and Cu have enriched in plant tissue and established a favorable link with Si.

Dragisic et al. [68] also reported that the Mn content in cucumber leaves treated with 100 µM was 10–40 times greater than the optimum. Even though, no toxicity symptoms of Mn have appeared in cucumber plants treated with Si, compared to non-Si applied plants. The root, as well as shoot biomass of plants, was increased with the application of Si. Teixeira et al. [69] revealed that plants showed lower Fe concentration when not treated with Si. However, the application of Si improved the Fe concentration in different parts of the sorghum. This might be due to the potential role of Si on Fe redistribution within the plant system. This could have been prompted by the process, in which Si reduced the occurrence of callose (plant polysaccharide important for permeability of plasmodesmata) in conducting vessels, allowing the motion of Fe in the phloem [70]. The increased Fe concentration in plants by Si application might be due to rhizosphere acidification [71–72]. Moreover, Nikolic et al. [73] reported that Si also helps in Fe uptake in plants by siderophore release mechanism of roots.

3.9 Nutrient use efficiency (NUE)

The PFP_{Si+P} of AR were found to decrease with increasing levels of P and Si (Table 6). Among the P levels, application of 30 kg P_2O_5 ha^{-1} recorded the highest PFP_{Si+P} followed by 60 kg P_2O_5 ha^{-1}. Similarly, among the Si levels, the highest PFP_{Si+P} were recorded in 40 kg Si ha^{-1} followed by 80 kg Si ha^{-1}. Among the P and Si levels, the lowest PFP_{Si+P} were recorded in 90 kg P_2O_5 ha^{-1} and 120 kg Si ha^{-1}, respectively. Similar to PFP_{Si+P}, the AE_{Si+P} was found to decrease with increasing doses of P and Si. However, it remained significant only in Si levels. Among the Si levels, the significantly higher AE_{Si+P} was recorded in 40 kg Si ha^{-1} followed by 80 kg Si ha^{-1} while the lowest was recorded in 120 kg Si ha^{-1}.

The physiological efficiency of applied P and Si was found significant (Table 6). The highest P physiological efficiency was recorded in 30 kg P_2O_5 ha^{-1}. Increasing P dose from 60 to 90 P_2O_5 ha^{-1} reduced P physiological efficiency significantly. It shows 60 kg P_2O_5 ha^{-1} is optimum for higher yield and physiological efficiency of P. Among the Si levels, the highest P physiological efficiency was recorded in 40 kg Si ha^{-1}. Increasing Si dose from 80 to 120 kg Si ha^{-1} significantly reduced the P physiological efficiency. Thus, the P and Si levels at 60 and 80 kg ha^{-1} respectively, are optimum for higher physiological efficiency of P.

Improved source-sink equilibrium, better economic yield, and adequate nutrient uptake might be the reason for high PFP, AE, and physiological efficiency observed with Si and P application. Photosynthetic potential of top leaves and coordinated distribution of sunlight and nutrients are synergistically correlated to nutrient utilization efficiency [74–75]. Enhanced physiological efficiency with application of Si and P indicated improved efficiency of the plant to transform nutrient grasped by plant into grain and this may be owing to increased photosynthesis rate and sink capacity. Recent, it has been reported that Si takes part in primary metabolism and amino acid remobilization [76–77] relating to increased nutrient demand by the grains.

3.10. PCA and correlation study

The PCA comprising two principal components (PC 1 and PC 2) accounted for ~79% of the variance with different treatment combinations. An angle of 0 or 180° reflects a correlation of 1 or —1, respectively. The interpretation of PCA results can be described by the positioning of the different variables and superimposition of respective PCA plots for respective treatment combinations as shown in the biplot (Figure 8). The superimposition of individual plots comprising various treatments (Si and P) on variables plot showed that AR treated with the higher dose of Si and P represents a higher correlation with DMA, nutrient uptake, and grain yield. The position of a total of 13 parameters of plant yield and nutrients accumulation was influenced by various treatments combination. Similarly, correlation among various variables such as DMA, nutrient uptake, and grain yield was presented in fig 9. All the variables showed a positive and significant correlation with each other at $p \leq 0.05$ (Figure 9).

4 Conclusions

The results reveal that co-fertilization of 90 kg P_2O_5 and 120 kg Si ha^{-1} as basal application, is beneficial in enhancing the DMA, grain yield, and NUE in AR. The results highlight importance of Si application in enhancing P uptake under aerobic rice cultivation. This study has also shown a strong positive correlation between Si with other essential nutrients (N, P, K, Mn, Cu, and Fe) suggesting improving nutrient uptake and increased applied NUE with the application of Si. Further studies are still required to comprehensively understand the effects of Si and P on soil fertility and crop productivity of aerobic rice under variable moisture conditions and along with P and Si-solubilizing bacteria.

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Compliance with Ethical Standards

Conflict of Interest: The authors declare that there is no potential conflict of interest.

Consent to participate: Informed consent was obtained from all individual researchers engaged in the experiment.

Consent for publication: The authors have consented for the submission of this research paper to the journal.

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Authors contribution:

Conceptualisation: [Dinesh Jinger; Shiva Dhar; Anchal Dass; VK Sharma]; Methodology: [Dinesh Jinger; Vijayakumar S; Gaurendra Gupta]; Formal analysis: [Dinesh Jinger; Manoj Parihar]; Investigation: [Dinesh Jinger; Shiva Dhar]; Writing–original draft: [Dinesh Jinger; VK Sharma; Manoj Parihar]; Writing-review and editing: [Anchal Dass; Vibha Singhal; Venkatesh Paramesh; Ekta Joshi]; Supervision: [Dinesh Jinger; Gaurendra Gupta]; Funding acquisition: [Dasharath Prasad; Ekta Joshi; Vibha Singhal]; Resources: [Vijayakumar S; Dasharath Prasad; Venkatesh Paramesh]

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Figures

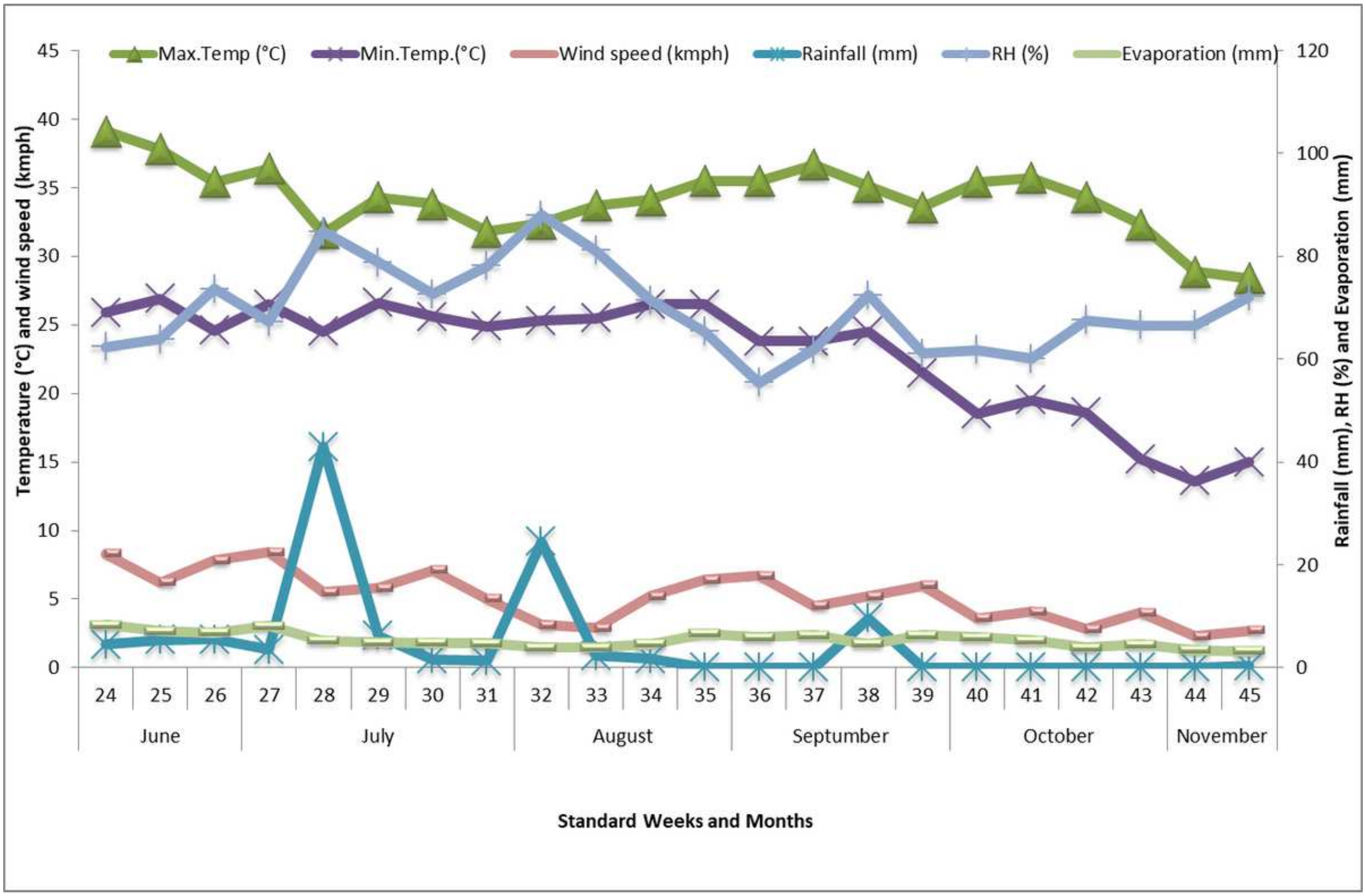

Figure 1

Weather parameters during crop season (2015)

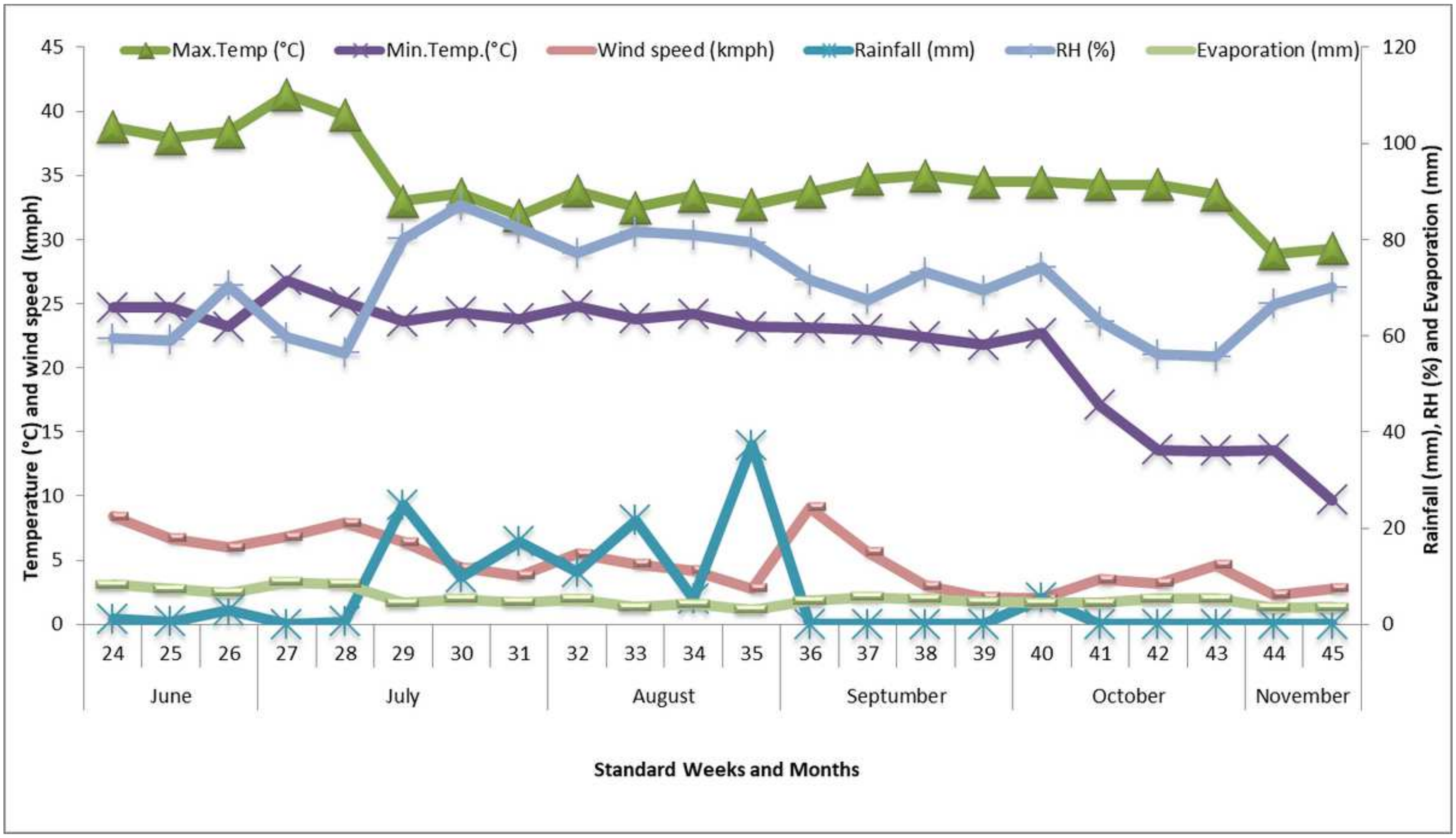

Figure 2

Weather parameters during crop season (2016)

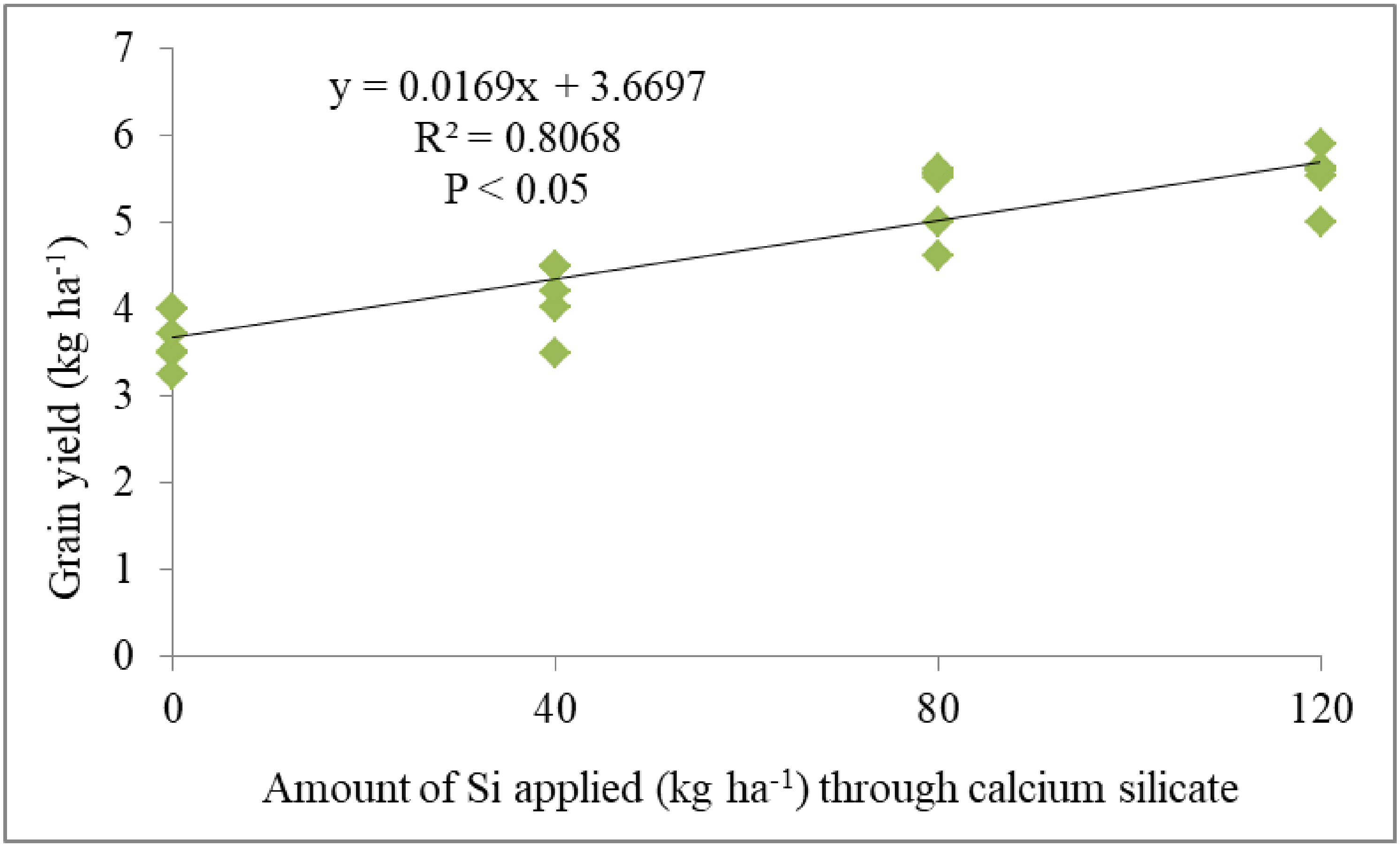

Figure 3

Linear regression between Si application and grain yield of AR

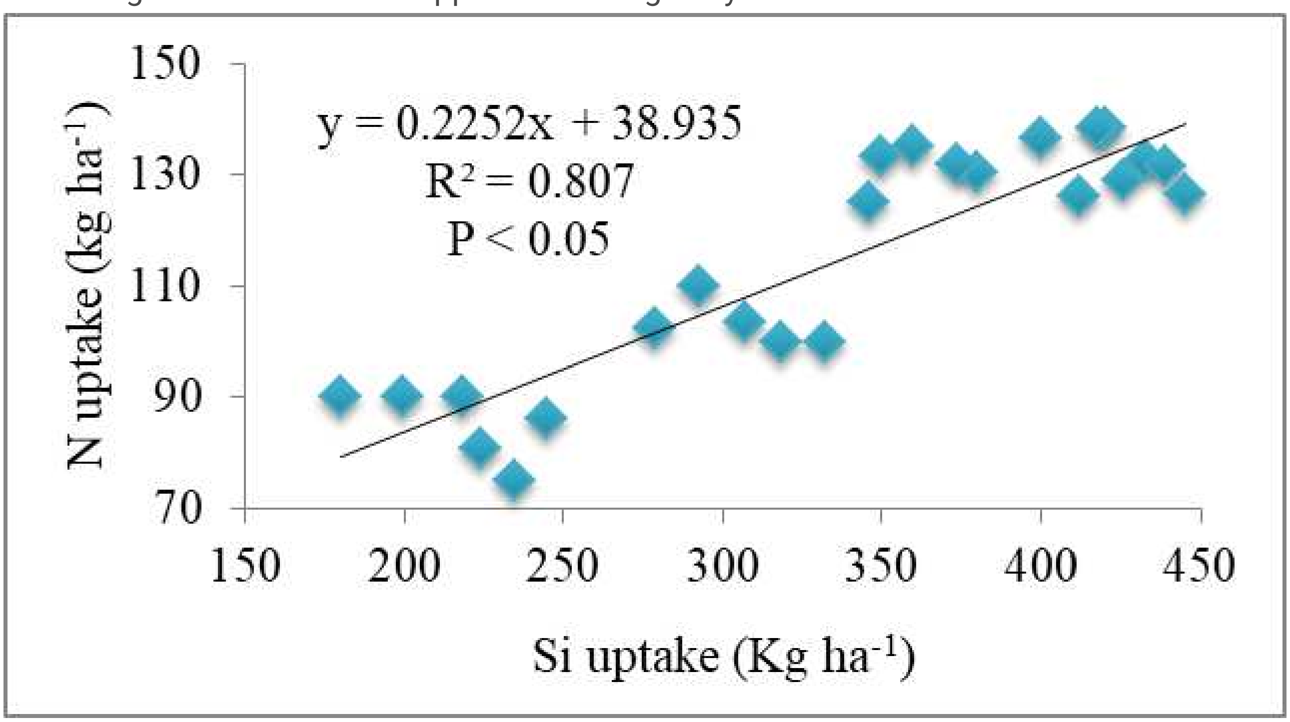

Figure 4

Linear regression between Si and N uptake of AR

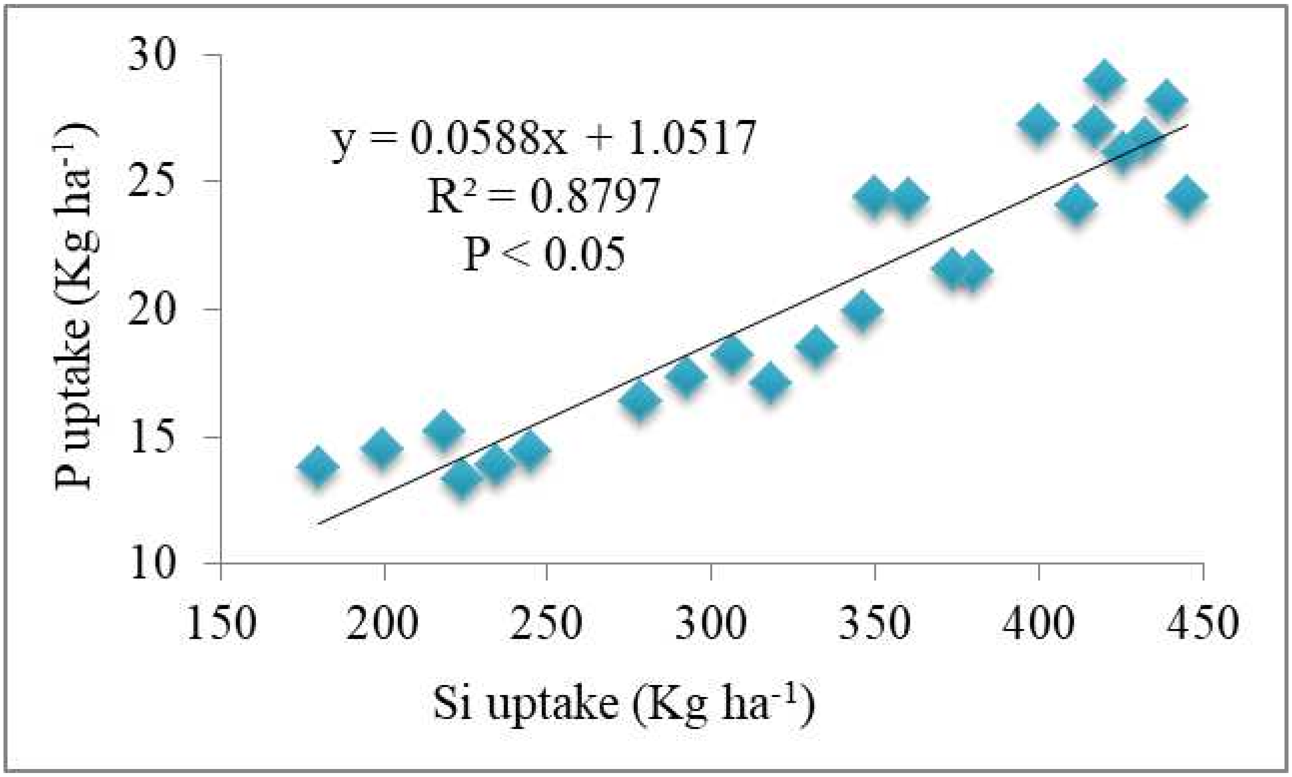

Figure 5

Linear regression between Si and P uptake of AR

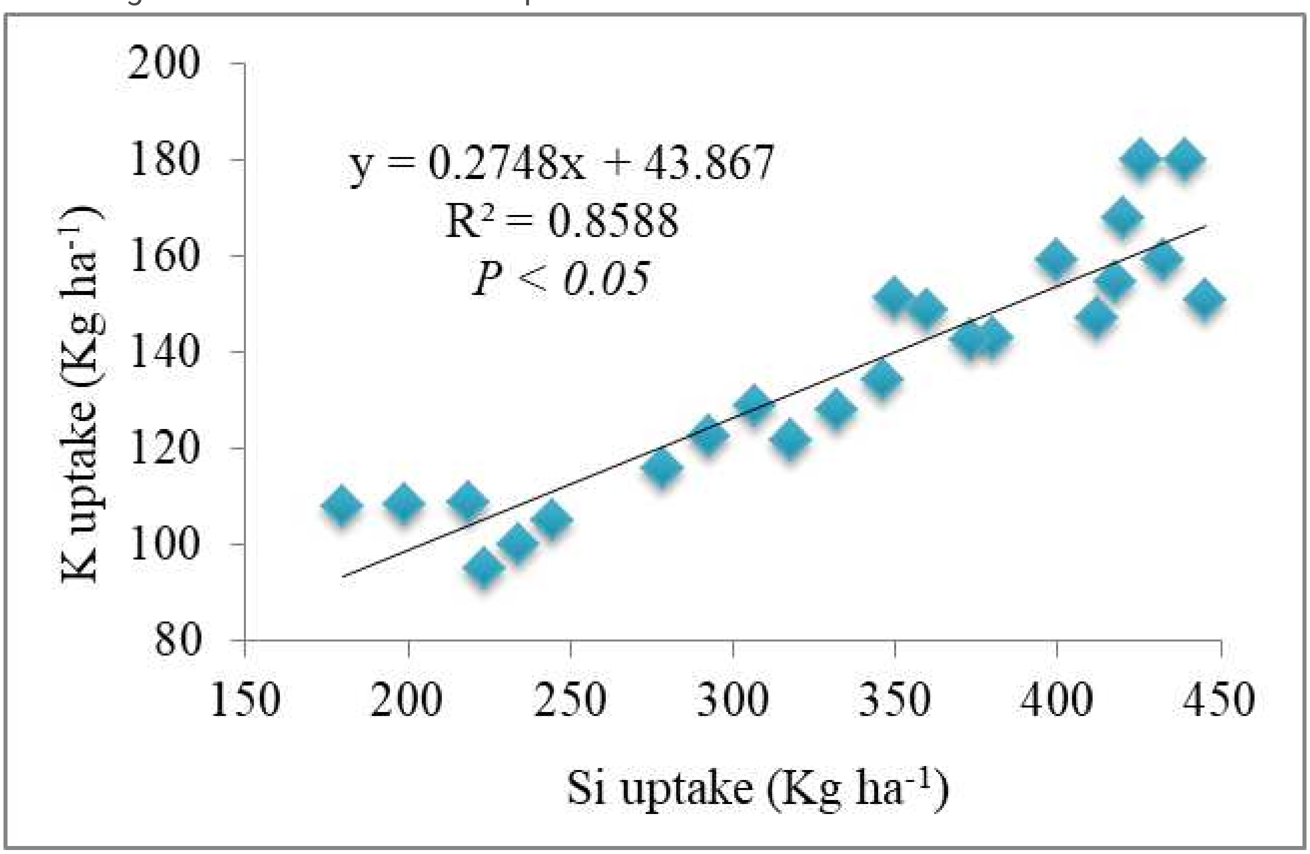

Figure 6

Linear regression between Si and K uptake of AR

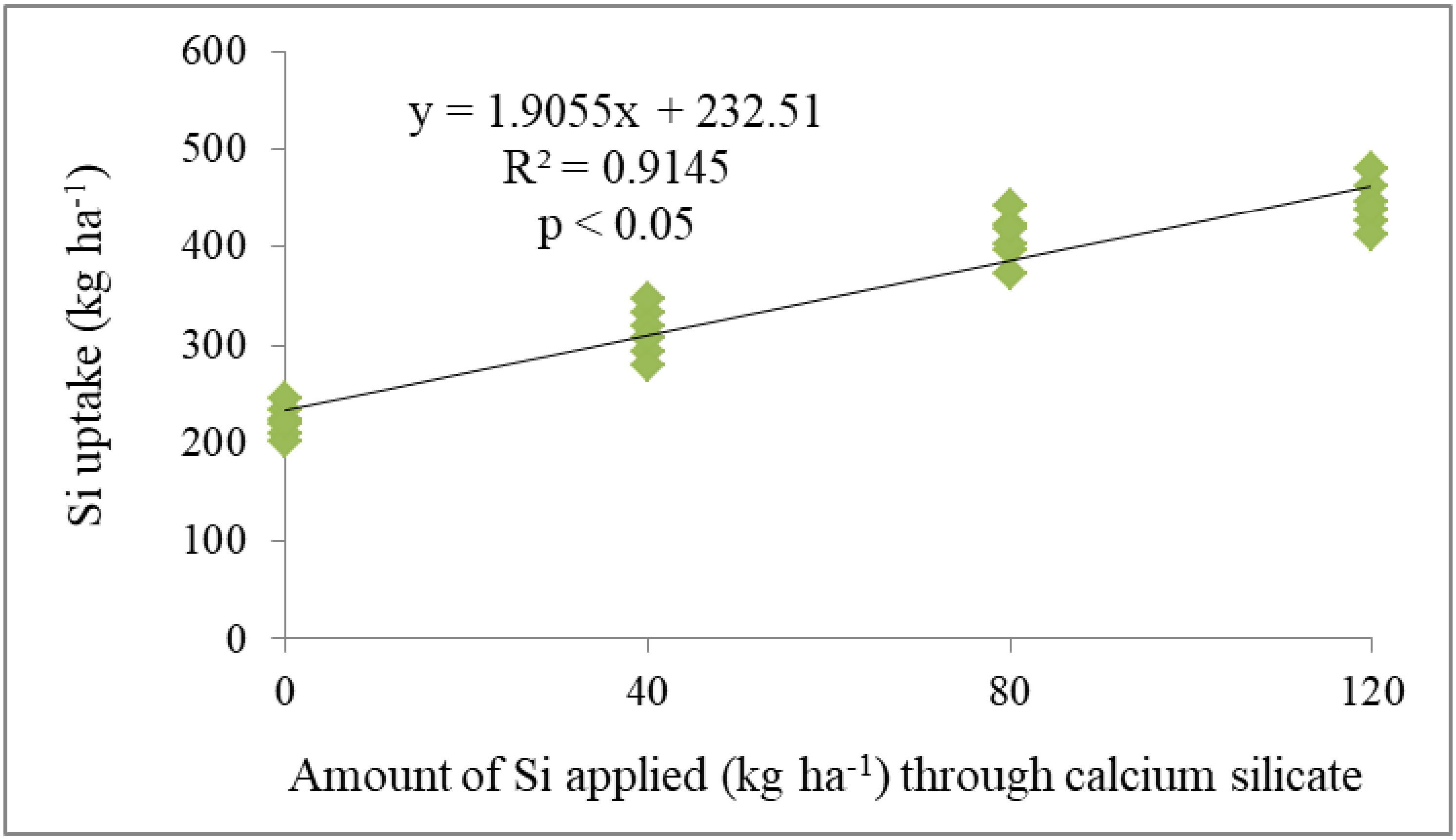

Figure 7

Linear regression between Si applications on Si uptake of AR

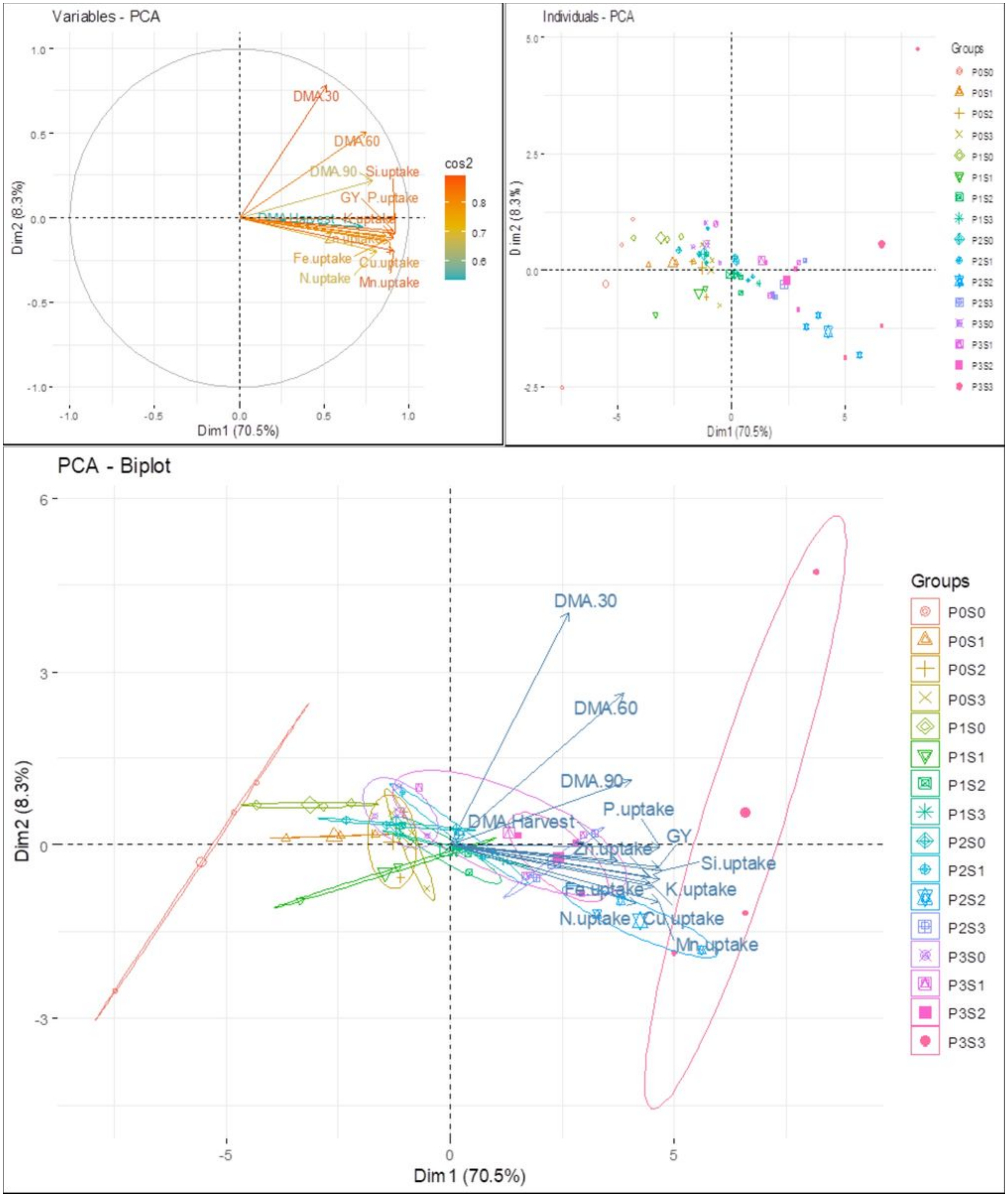

Figure 8

Ordination diagram of principal component analysis showing the effects of Si and P on DMA, grain yield and nutrient uptake. The small angle between vectors (arrow) and higher length represent greater correlation between the variable; P0 = no P2O5; P1 = 30 kg P2O5 ha−1; P2 = 60 kg P2O5 ha−1; P3 = 90 kg P2O5 ha−1; S0 = no Si; S1 = 40 kg Si ha−1; S2 = 80 kg Si ha−1; S3 = 120 Si ha−1.

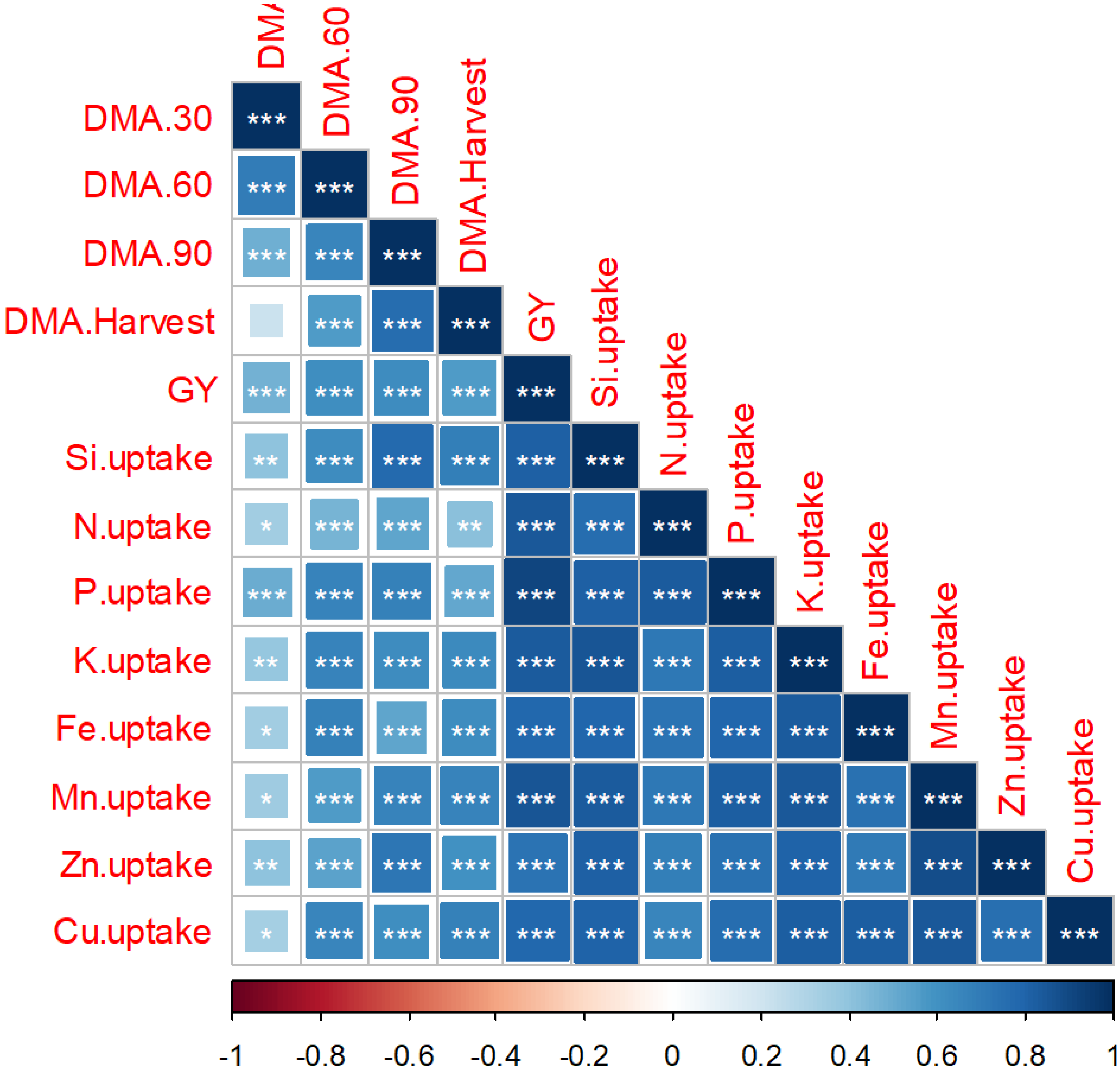

Figure 9

Correlation matrix among different variables the blue colour corresponds to (+) positive interaction and red color correspond to (−) negative interaction and white correspond to neutral interaction between variables. Significance codes: * p ≤ 0.05; ** p ≤ 0.01; *** p ≤ 0.001.