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RESEARCH

Phosphate Fertilization Mediated Agronomic Enhancement of Banana Cultivars Using Multivariate Biplot Methodology

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ABSTRACT

Purpose: *Banana (Musa spp.) always possesses a prominent position in our daily diet due to its astounding nutrition profile and medicinal potential bioactive compounds. An investigation was carried out in the northern region (Bogura district) of Bangladesh to explore the effect of differential phosphate fertilization levels on bunch attributes and fruit yield parameters of three banana cultivars: Grand Naine, Champa and Anupom.*

Research Method: *Five TSP rates (0, 200, 300, 400 and 500 g plant-1 TSP) were evaluated in this study for two production cycles with the aid of GT (Genotype X Trait) biplot methodology.*

Findings and Values: *The findings implied that all three cultivars exhibited a consistent increment in the magnitude of all bunch attributes and shorter phenological cycle (days from planting to flower emergence and days from flower emergence to harvesting) as a response to the ascending P fertilization, which culminated in 400 g plant-1 TSP rate. The responsiveness to P fertilization was more conspicuous in the cultivar Grand Naine as revealed by more pronounced enhancement in bunch attributes. A longer phenological cycle and drastic declines in all bunch and yield parameters were observed in all three cultivars at a 500 g plant-1 TSP rate, indicating the detrimental effect of excessive Phosphate application beyond the specific threshold. All three cultivars showed higher productivity across all bunch traits in the second production cycle than in the first. This study signifies the judicious determination of P fertilization for lessening of excess P-mediated soil toxicity, nutrient deficiency and disease incidence in banana for the northern region of Bangladesh.*

Keywords: *Banana, GT Biplot, Multivariate analysis, Phosphate fertilization.*

INTRODUCTION

Banana (*Musa spp.*) is well recognized as one of the prominent dietary sources among major fruit crops, native to Southeast Asia and deliberately grown worldwide for its outstanding nutritional and phytochemical profile (Fuller & Madella 2009, Borges *et al.* 2020, Lopes *et al.* 2020). This perennial herbaceous monocot from Musaceae possesses immense health benefits and therapeutic potentiality, which not only acts as a defensive shield for reinforcing our food and nutrition security, but its commercial cultivation also provides a handsome economic return (Qamar & Shaikh 2018, Mohd Zaini *et al.* 2022, Choudhury *et al.* 2023).

Bangladesh produced 826179 metric tons of bananas from 49609 ha of cultivated area in the year 2022–23 and ranked among the top 30 banana producing countries of the world (FAOSTAT 2024). *Champa, Shabri, Kabri, Mehersagar, Dudhsagar, Amritosagar,*

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Agniswar, Genashundari, Kanaibanshi, Basrai, Binishuta are the most prevalent banana cultivars in Bangladesh and are considered as one of the major fruit crops and an indispensable part of the daily diet (Mukul & Rahman 2013).

The ultimate improsaraffi@bau.edu.bdt in yield and quality attributes of banana has always been the cumulative contribution and coordination of genetic excellence and agronomic precision. Phosphate (P) fertilization is considered as one of the vital but nearly overlooked management practices for banana cultivation, as banana generally possesses a huge demand for nitrogen (N) and potassium (K) nutrition (Mustaffa & Kumar 2012). Consequently, literature highlighting the effect of P nutrition on yield parameters and bunch attributes of banana is somewhat scarce in mainstream research journals compared to studies reflecting the effect of N and K. Phosphorus plays a pivotal role in energy storage and transfer during photosynthesis, root growth and expansion, and several regulatory pathways as a cellular component. Its deficiency leads to severe growth stunting (Shen *et al.* 2011, Zhang *et al.* 2014). Silva & Rodrigues (2013) observed a linear increase in bunch attributes of *"Prata ana"* banana in P-deficient Brazilian clayey red latosol as a result of augmented phosphate application.

Leonel *et al.* (2020b) reported a quadratic response of *"FHIA 18"* hybrid to P fertilization in several fruit yield parameters under Brazilian edaphoclimatic conditions. Similar quadratic increments in bunch characteristics were observed in several banana cultivars by Liu *et al.* (2015) in response to phosphorus application. Al-Harthi & Al-Yahyai (2009) exhibited P fertilization-mediated linear fruit yield increase in *"Williams"* banana cultivar in sandy soil of Oman. However, the perspective of P fertilization effects on bunch and yield parameters in prevailing banana cultivars of Bangladesh is narrowly explored, which persuaded us to devise this investigation.

Moreover, indiscriminate use of inorganic P fertilizers without maintaining proper dose may induce soil toxicity-mediated yield reduction due to drastic Zn deficiency, reduction of soil pH through formation of insoluble Fe and Al complexes, and disease incidence (Rohily *et al.* 2013, Bolan *et al.* 2015, Ova *et al.* 2015, Fallah Nosratabad *et al.* 2017, Leonel *et al.* 2020a).

GT (genotype $\times$ trait) biplot analysis has recently gained momentum in breeding and agronomic investigations due to its precise portrayal of embedded multivariate trait association patterns and trait responses to particular environmental stimuli with the aid of an intuitive graphical interface. This approach generates incisive and insightful inferences about system-level crop understanding (Yan & Kang 2002, Yan & Rajcan 2002). Recognizing this knowledge gap, the present investigation was devoted to attaining constructive insight into the multifold impact of different P fertilization levels on bunch and fruit yield attributes of banana cultivars in Bangladesh for formulating an effective and sustainable P nutrient management strategy.

MATERIALS AND METHODS

Experimental site

The field experiment was carried out at the experimental farm of TMSS (*Thengamara Mohila Sabuj Sangha*—a Bangladeshi non-profit organization working for women empowerment) regional station at *Shibgonj Upazilla* (24°54'–25°08' N, 89°10'–89°28' E) of *Bogura* District, Bangladesh. The region experiences a tropical monsoon climate with an annual average temperature of 25.9°C. The annual average precipitation was 1775 mm and the average monthly maximum and minimum temperatures were 30.7°C and 20.9°C, respectively. The experimental site falls under the *AEZ* (Agro-ecological Zone) of the *Tista Meander Floodplain*.

The soil was classified as Typic Haplaquepts under the Inceptisols order according to the USDA soil classification system and belongs to non-calcareous grey floodplain soil along with *Tista* silt soil tract (Huq & Shoaib 2013). The soil texture was silty clay loam with 1.2% organic matter, 0.06% N, 96.97 μg g^{-1} P, 0.22 μg g^{-1}

K, 0.80 μg g^{-1} Zn, 27.74 μg g^{-1} S, 0.22 μg g^{-1} B and pH 5.7.

Phosphate fertilization and nutrient management

The land was prepared by applying adequate amounts of N, K, S, Zn, B and organic matter as per local production recommendations and soil analysis. All necessary agronomic management practices and intercultural operations were followed according to cultivation recommendations. Phosphate fertilization was incorporated in five doses: 0 g plant^{-1} (control, P_1), 200 g plant^{-1} (P_2), 300 g plant^{-1} (P_3), 400 g plant^{-1} (P_4) and 500 g plant^{-1} (P_5) in the form of TSP (Triple Super Phosphate, 20% P), equivalent to 0, 40, 60, 80 and 100 g plant^{-1} P. Complementary fertilizers were applied as N (230 g plant^{-1}), K (300 g plant^{-1}), S (36 g plant^{-1}), Zn (1.2 g plant^{-1}), and B (0.34 g plant^{-1}) in the form of urea, potassium chloride, gypsum, zinc sulphate and boric acid, respectively. Organic matter was added at 5 kg per pit. Half of the P and organic matter, along with all S, Zn and B, were applied in the pit 10 days before planting as basal application. The remaining half of P and organic matter were broadcast during final land preparation. Nitrogen and K fertilizers were top-dressed in four splits, with the first application 2 months after planting, the second and third at two-month intervals, and the last after inflorescence emergence. Proper precautionary measures were taken during fertilizer application to avoid health hazards.

Three banana cultivars were selected: *Grand Naine* (AAA) from the *Cavendish subgroup, Champa* (AAB), and *Anupom* (AAB) from the *Horn plantain* subgroup (Lopes *et al.* 2020). Two production cycles were evaluated. For *Grand Naine*, the first cycle spanned February 2021 to May 2022 and the second July 2022 to August 2023. For *Champa*, the first cycle lasted February 2021 to June 2022 and the second August 2022 to November 2023. *Anupom*'s first production cycle occurred from February, 2021 to July, 2022 and the second cycle had taken place from September, 2022 to January, 2024. Micro propagation derived two months old seedlings were planted with 2.5m X 2.5m spacing.

Bunch morphological attributes

The bunch morphological parameters evaluated were plant height (cm), girth (cm), number of hands per bunch, number of fingers per hand, number of fingers per bunch, inflorescence length (cm), peduncle length (cm), bunch length (cm), fruit length (cm), fruit diameter (cm), fruit weight (g), pulp–peel ratio, days from planting to flower emergence, and days from flower emergence to harvesting. Measurements were recorded following the methods described by Leonel *et al.* (2020a) and Bolfarini *et al.* (2020).

Experimental design and statistical analysis

The experimentation was performed following RCBD design with three replications for three cultivars and five P fertilization rate resulting in 15 (P dose X cultivar) treatments randomized in each of the 3 blocks. Three plants were assigned for each cultivar totaling 45 randomized plants with five P fertilization treatments per block. Analysis of variance (ANOVA) and Tukey's HSD test were performed for multiple comparisons of different cultivar-P rate combination on all of the bunch and fruit yield attributes. A GT biplot analysis was conducted to visualize the trait and cultivar specific response pattern to P fertilization and their interrelationship between them. GT biplot was based on the following formula.

$$\frac{T_{ij} - \bar{T}_j}{s_j} = \lambda_1 \xi_{i1} \eta_{1j} + \lambda_2 \xi_{i2} \eta_{2j} + \varepsilon_{ij}$$

where T_{ij} is the value of trait j of genotype i, $\bar{T}_j$ is the average of trait j across all cultivars, s_j is the standard deviation of trait j across all cultivars, λ_1 and λ_2 are the singular values for PC1 and PC2, respectively, ξ_{i1} and ξ_{i2} are the PC1 and PC2 scores for cultivar i, η_{1j} and η_{2j} are the PC1 and PC2 scores for trait j, and ε_{ij} is the residual associated with cultivar i and trait j. Trait-standardized data were subjected to singular value decomposition (SVD) to generate PC1 and PC2 scores for cultivars and traits. These were used to construct biplots by plotting

PC1 scores against corresponding PC2 scores. All statistical and GT biplot analyses were performed using R (version 4.3.2) and its multiple package utilities (Frutos *et al.* 2014, R Core Team 2024).

RESULTS AND DISCUSSION

Cultivar-specific responses to P fertilizer

The variability in response pattern of banana cultivars to different P fertilization rates in relation to bunch attributes facilitates with comprehensive insight about determination of appropriate dose for particular cultivar and responsiveness of cultivars to P fertilization. This perspective is precisely portrayed through intuitive graphical interface in the polygon view of the biplot, evinced in the Fig. 1 to Fig. 3. The variance explained by the first two PCs (PC1 and PC2) of these biplots are above 93% indicating the excellent approximation of standardized P rate X Trait two-way datasets, hence underpins the any decisive interpretation discerned from the biplots. The P rate X Bunch traits two-way datasets were standard deviation standardized for erasing the discrepancy emanating from being measured in different units. All of these datasets were then trait centered (centering: 2) before subjecting to symmetrical singular value partitioning method (SVP: symmetrical), considered as conducive illustration platform for meaningful visualization of both P rate and bunch attributes relative to PC1 and PC2. In the polygon view of the biplot, the formation of polygon is facilitated by connecting the vertex points representing P rate resulting in a convex hull.

The perpendicular line drawn to the sides of the convex hull delineates contrasting comparison between the different P rates in terms of the extent of various bunch attributes for specific cultivars. The differential magnitude of trait levels in response to five P fertilization rates for the cultivar *Grand Naine* for two production cycles are manifested in the Fig. 1A and Fig. 1B. In Fig. 1A, it is somewhat conspicuous that all of the traits but the days to flower emergence from planting (days from planting to flower emergence) and days to harvesting from flower emergence (days from flower emergence to harvesting) are positioned in the sector where 400 g plant$_{-1}$ TSP rate represents the apex P rate depicting that all of these traits reached their highest magnitude at the TSP rate of 400 g plant$_{-1}$ for *Grand Naine* cultivar in the first production cycle. It also indicates that the *Grand Naine* needed lesser days to reach flower emergence from planting (239 days) and had a shorter span (75 days) between flower emergence and harvesting in comparison to other TSP rates.

As 300 g plant$_{-1}$ TSP rate is also found to be fallen in the same sector of 400 g plant$_{-1}$ TSP rate, it indicates that the second highest level was achieved by all of these traits at this TSP rate next to 400 g plant$_{-1}$ TSP rate. This can also be corroborated from the numerical data presented in Table 1. Similar pattern of trait response in relation to five TSP rates for *Grand Naine* was observed in the second production cycle although trait relationship pattern was seemed slightly different in comparison to first production cycle as revealed by the Fig. 1B. This finding is somewhat in well concordance with the findings of Bhalerao *et al*. (2009) and Leonel *et al*. (2020a) as they also found *Grand Naine* exhibiting superior performance in majority bunch attributes and fruit yield parameters in response to ascending P fertilization although the TSP rate for attaining the highest magnitude was slightly different. The main cause of this discrepancy derived from these findings can be ascribed to the variability of the soil types and properties on which the soil P nutrient dynamics rely, leading to variable TSP rate optimization. Fig. 2A and Fig. 2B represent the variability in the trait response scenario of cultivar *"Champa"* to five different P fertilization rates for two production cycles. It can be well perceived from the observed scenario that most of the trait points except the days from planting to flower emergence (310 days) and days from flower emergence to harvesting (84 days) belong to the sector where P400 g plant$_{-1}$ is the vertex TSP rate, indicating the TSP rate at which these traits reached their peak of magnitude. The presence of 300 g plant$_{-1}$ TSP rate in the same sector depicts the TSP rate responsible for attaining their second highest level. This similar trend of trait response to five P fertilizer rates is visible in Fig. 2B for the second production cycle of the cultivar *"Champa"*. This pattern of trait response can also be substantiated from the numerical mean data in Table 1. The main effect of five P fertilizer rates and their interaction with the cultivar *"Anupom"* in terms of the magnitude of different bunch attributes for the two production cycles are graphically portrayed in the Fig. 3A and Fig. 3B. It can be somewhat well discerned from the above figures that all of the traits but days from planting to flower emergence (341 days) and days from flower emergence to harvesting (88 days) attained their highest level at the 400 g plant$_{-1}$ TSP rate in the first production cycle and this similarity of the trait response pattern was followed in second production cycle with a trivial non-significant alteration in the trait relationship. A common trend perceived from this cultivar-specific graphical portrayal of response to five P fertilizer rates was that all three cultivars exhibited the highest magnitude of trait response at the 400 g plant$_{-1}$ TSP rate. Interestingly, this increment in the level of all bunch attributes but days from planting to flower emergence and days from flower emergence to harvesting of all three cultivars followed a sharp decline at the 500 g plant$_{-1}$ TSP rate. In case of phenological cycle (days from planting to flower emergence and days from flower emergence to harvesting), relatively shorter temporal span was exhibited by the cultivar *Grand Naine* compared to the cultivar *Champa* and *Anupom* in response to gradual ascending TSP rates up to 400 g plant$_{-1}$, consistent with the findings of Taulya *et al.* (2014) and Leonel *et al.* (2020a).

Nevertheless, the overall pattern, summarized from the *polygon view* of the biplot in Fig. 1 to Fig. 3, indicates that increasing TSP rate up to a certain level invokes a higher magnitude of trait response. The noteworthy enhancement in bunch traits and fruit yield characteristics in response to incremental P amendments up to 400 g plant^{-1} TSP rate may be attributed to rapid augmentation of photosynthesis through upregulation of major photosynthesis and sucrose biosynthesis genes. Phosphorus plays a key role in energy transfer, nucleic acid synthesis, redox reactions and carbohydrate metabolism (Schachtman *et al.* 1998, Shen *et al.* 2011, Cai *et al.* 2013, Zhao *et al.* 2015).

Trait-specific responses to P fertilizer

The responsiveness of various bunch attributes of three banana cultivars to five different P fertilization rates provides an elaborative outlook on the magnitude of variation imposed by fertilization, thereby facilitating development of trait-specific efficient P fertilizer management strategies. The extent of response of different bunch attributes to five TSP rates for three banana cultivars across two consecutive production cycles is illustrated through the polygon view of the biplot in Fig. 4A and Fig. 4B. The ATC (average trait coordination) view of the biplot, shown in Fig. 5A and Fig. 5B, enhances understanding of responsiveness patterns of bunch traits to different TSP rates for each cultivar. More than 90% of the total variation was explained by the first two principal components (PC1 and PC2), reinforcing the validity of interpretations derived from biplot theory.

In the ATC view, the arrow represents the position of the average bunch trait coordinate. The line passing through the biplot origin and the average trait coordinate is termed the "ATC abscissa". A longer projection of a cultivar–P rate combination onto the "ATC abscissa" indicates a higher magnitude of mean trait response toward the direction of the average trait coordinate. The perpendicular line through the origin to the "ATC abscissa" is termed the "ATC ordinate" and the displacement towards either direction of "ATC ordinate" implies deviation from the average trait responsiveness to cultivar-wise specific trait response for P rate-cultivar combination. Symmetrical method of singular value partitioning in the ATC view of the biplot allows us to cast equal focus on both the treatment combination and the trait, hence providing conducive visualization for meaningful comparison. The ATC ordinate also serves as an intuitive partition between the above-average and the below-average treatment combinations across all traits and provides a superiority ranking on the basis of that magnitude. It is pretty obvious from the polygon

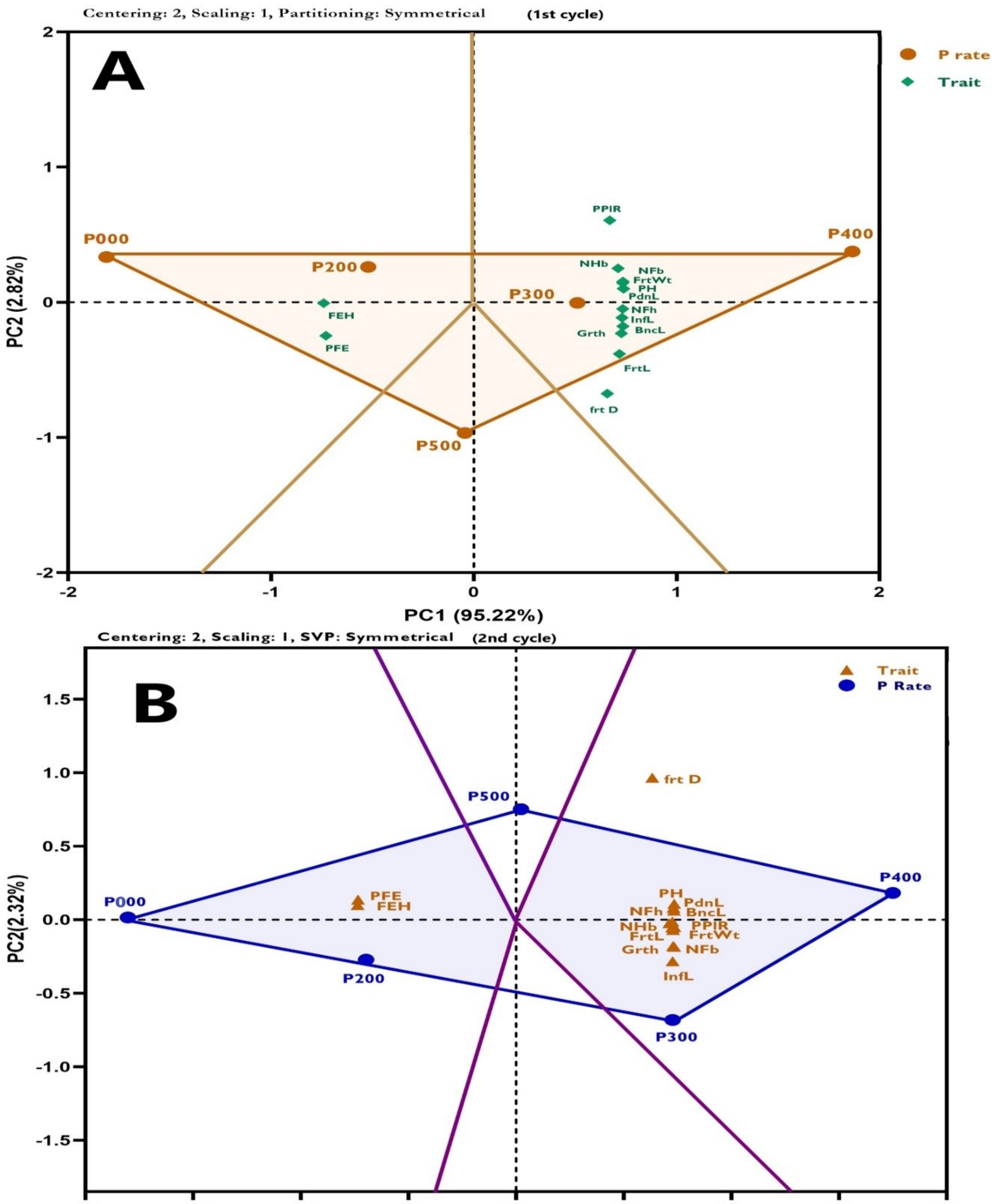

Figure 1. Polygon view of the biplot showing cultivar specific trait response to five P rates (P00= 0, P200= 200, P300= 300, P400= 400, P500= 500 g plant^{-1} TSP): (A) in first cycle and (B) in second cycle for Grand Naine which indicates the superiority of the 400 g plant^{-1} TSP rate. Here, PH= plant height, Grth= girth, NHb= number of hand per bunch, NFh= number of finger per hand, NFb= number of finger per bunch, InfL= inflorescence length, PdnL= peduncle length, BncL= bunch length, FrtL= fruit length, FrtD= fruit diameter, FrtWt= fruit weight, PPlR= pulp-peel ratio, PFE= days from planting to flower emergence and FEH= days from flower emergence to harvesting. PC= Principal component.

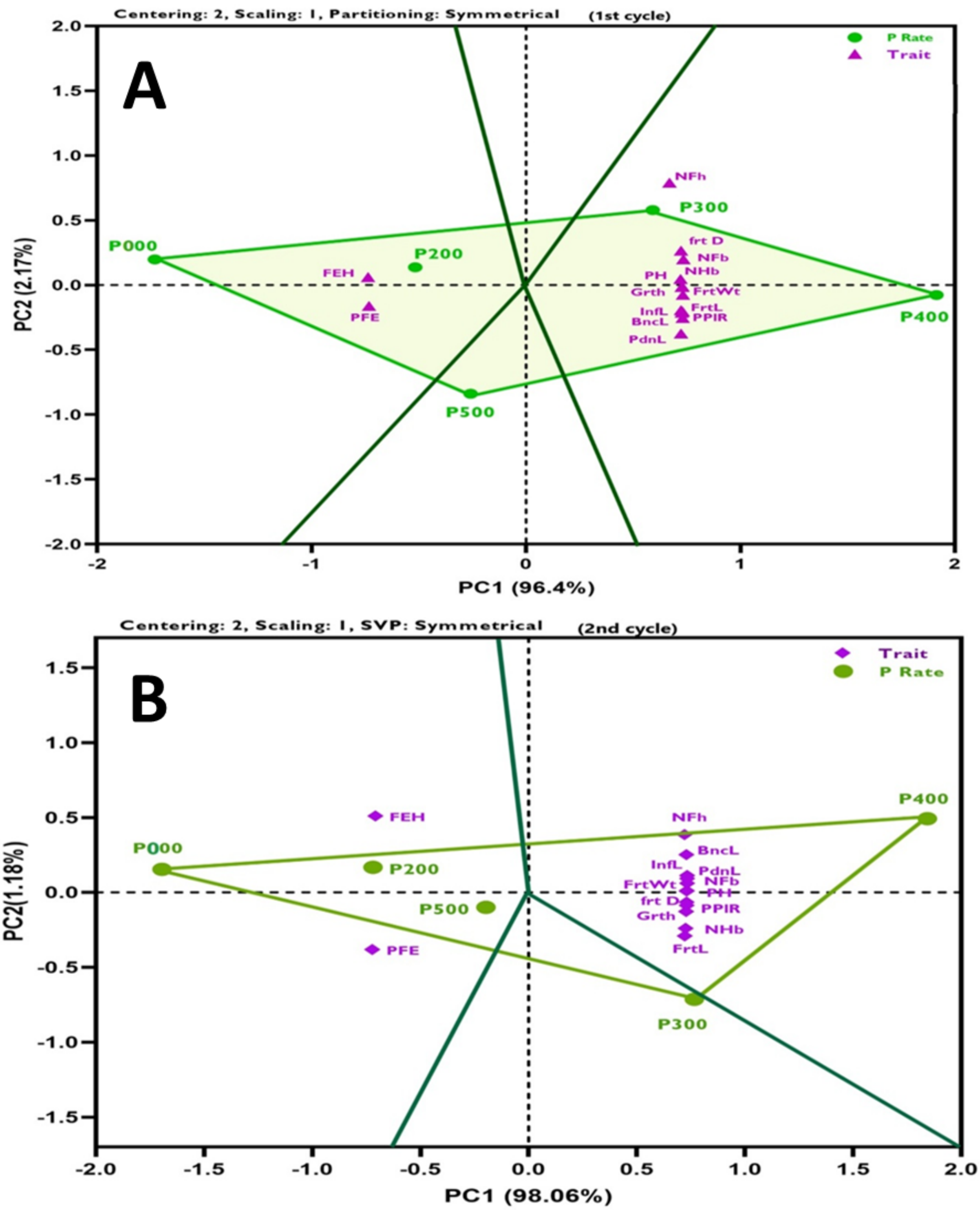

Figure 2. Polygon view of the biplot showing cultivar specific trait response to five P rates (P00= 0, P200= 200, P300= 300, P400= 400, P500= 500 g plant$_{-1}$ TSP): (C) in first cycle and (D) in second cycle for Champa, which indicates the superiority of the 400 g plant$_{-1}$ TSP rate. Here, PH= plant height, Grth= girth, NHb= number of hand per bunch, NFh= number of finger per hand, NFb= number of finger per bunch, InfL= inflorescence length, PdnL= peduncle length, BncL= bunch length, FrtL= fruit length, FrtD= fruit diameter, FrtWt= fruit weight, PPlR= pulp-peel ratio, PFE= days from planting to flower emergence, FEH= days from flower emergence to harvesting, PC= principal component.

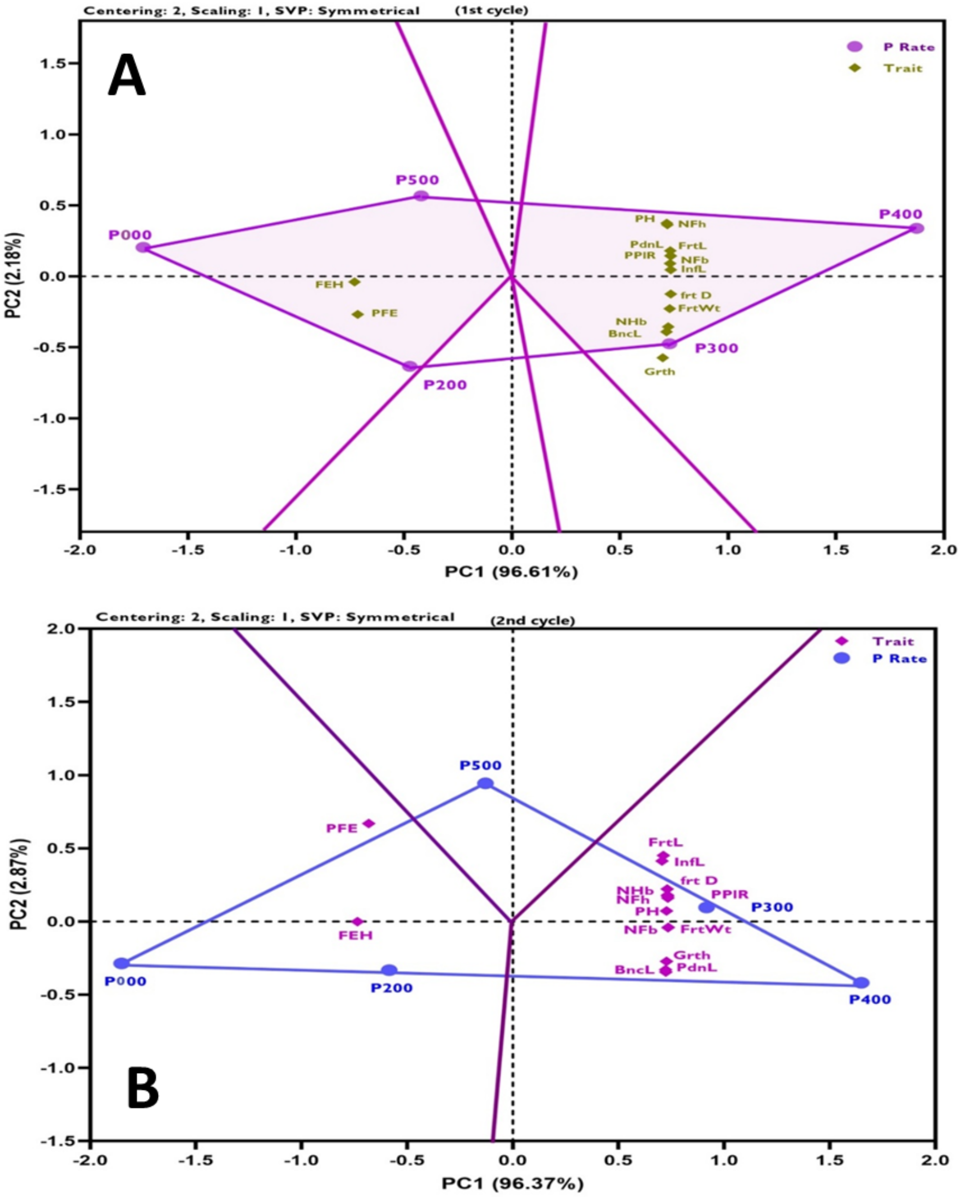

Figure 3. Polygon view of the biplot showing cultivar specific trait response to five P rates (P00= 0, P200= 200, P300= 300, P400= 400, P500= 500 g plant$_{-1}$ TSP): (E) in the first cycle and (F) in the second cycle for Anupom, which indicates the superiority of the 400 g plant$_{-1}$ TSP rate. Here, PH= plant height, Grth= girth, NHb= number of hand per bunch, NFh= number of finger per hand, NFb= number of finger per bunch, InfL= inflorescence length, PdnL= peduncle length, BncL= bunch length, FrtL= fruit length, FrtD= fruit diameter, FrtWt= fruit weight, PPlR= pulp-peel ratio, PFE= days from planting to flower emergence, FEH= days from flower emergence to harvesting, PC= principal component.

Table 1. Mean bunch trait values of three banana cultivars in two production cycles under five P rates.

Cultivar	TSP rate gm/ plant	Plant height (cm)		Girth (cm)		Number of hand per bunch		Number of finger per hand		Number of finger per bunch	
		1st cycle	2nd cycle	1st cycle	2nd cycle	1st cycle	2nd cycle	1st cycle	2nd cycle	1st cycle	2nd cycle
Grand Naine	0	117.29 j	113.57 i	37.24 f	41.29 g	11.25 c	11.89 c	9.72 d-g	9.06 ef	112.89 d	117.24 d
	200	139.87 hi	135.85 hi	46.16 d	57.92 c	12.56 ab	12.01 c	10.87 b-d	10.29 d	133.85 c	141.65 c
	300	160.51 f-h	165.61 f-h	60.56 b	69.74 b	12.87 ab	13.84 ab	11.56 ab	12.48 ab	148.74 b	172.68 b
	400	190.52 de	198.12 d-f	70.00 a	77.75 a	13.62 a	14.45 a	12.31 a	13.02 a	167.68 a	188.26 a
	500	148.12 g-i	153.41 gh	56.07 c	60.46 c	12.23 bc	13.03 b	11.09 a-c	11.61 bc	135.63 c	151.32 c
Champa	0	177.69 ef	173.21 f-h	29.43 h	33.21 h	6.06 f	6.85 ij	9.07 f-h	9.12 ef	57.23 i	63.14 h
	200	209.26 cd	219.72 c-e	35.72 fg	40.19 g	7.69 e	7.48 hi	9.57 e-h	9.89 de	73.62 fg	75.45 gh
	300	240.01 b	270.25 b	40.79 e	47.33 ef	8.05 e	9.65 de	10.32 b-e	10.43 d	91.10 e	100.70 e
	400	303.75 a	312.83 a	44.64 d	51.49 d	9.50 d	10.45 d	10.45 b-e	11.53 c	107.01 d	120.43 d
	500	215.37 c	240.80 bc	37.02 f	41.35 g	7.32 ef	8.53 fg	9.24 e-h	10.16 d	73.81 fg	86.67 fg
Anupom	0	131.26 ij	139.24 hi	30.43 h	33.19 h	6.91 ef	6.11 j	6.41 j	6.22 h	43.26 j	41.28 i
	200	167.12 fg	189.27 e-g	36.78 f	39.46 g	7.45 e	7.21 i	7.52 ij	7.49 g	58.31 i	63.22 h
	300	199.59 cd	229.05 cd	39.89 e	44.64 f	7.93 e	8.37 f-h	8.80 gh	9.86 de	69.76 gh	82.53 fg
	400	250.35 b	274.59 ab	40.83 e	47.89 e	8.12 e	8.78 ef	10.22 c-f	10.73 cd	82.30 ef	94.16 ef
	500	188.58 de	212.78 c-e	34.55 g	38.70 g	7.31 ef	7.70 g-i	8.42 hi	8.74 f	61.57 hi	67.25 h
	CV (%)	3.67	6.43	1.30	2.29	4.53	3.38	4.23	2.98	3.58	3.99
	HSD	21.04	39.31	1.68	3.24	1.27	0.99	1.25	0.91	10.23	12.61

Cultivar	TSP (gm/plant)	Fruit weight (gm)		Pulp–peel ratio		Days from planting to flower emergence (PFE)		Days from flower emergence to harvesting (FEH)	
		1st cycle	2nd cycle	1st cycle	2nd cycle	1st cycle	2nd cycle	1st cycle	2nd cycle
Grand Naine	0	10.11 de	10.55 cd	3.96 cd	4.04 e-g	363.33 e	289.33 e	103.67 cd	98.33 c
	200	11.30 cd	11.63 bc	4.26 b-d	4.83 c-e	332.00 f	264.67 f	93.67 e-g	86.67 de
	300	12.20 bc	12.58 b	4.54 bc	5.78 ab	295.00 h	218.33 h	85.33 gh	75.00 fg
	400	14.36 a	15.78 a	5.77 a	6.65 a	238.33 i	190.00 i	75.00 i	65.00 g
	500	13.58 ab	14.65 a	4.18 b-d	5.19 b-d	321.67 fg	248.33 fg	90.00 f-h	83.00 ef
Champa	0	6.88 hi	6.72 h	1.75 g	1.82 k	396.33 bc	392.33 a	111.67 bc	109.33 ab
	200	7.63 g-i	7.55 f-h	2.19 fg	2.23 jk	372.33 de	357.67 b	103.33 c-e	98.00 c
	300	8.27 f-h	9.53 de	2.41 fg	3.29 g-i	335.00 f	315.00 d	93.33 fg	84.33 d-f
	400	9.33 ef	10.62 cd	2.92 ef	3.85 f-h	310.00 gh	247.00 g	83.33 hi	83.00 ef
	500	7.41 hi	8.08 fg	2.28 fg	2.58 i-k	365.00 de	339.00 c	99.33 d-f	94.33 cd
Anupom	0	6.22 i	6.89 gh	2.93 ef	2.98 h-j	426.00 a	404.67 a	127.67 a	112.67 a
	200	7.93 f-h	8.25 ef	3.47 de	3.89 fg	414.00 ab	369.67 b	118.33 ab	99.00 bc
	300	9.21 e-g	10.69 cd	4.25 b-d	4.96 b-d	383.00 cd	335.00 c	98.00 d-f	85.67 de
	400	10.29 de	11.45 bc	4.89 b	5.30 bc	340.67 f	306.67 d	87.67 gh	74.67 fg
	500	7.84 f-i	9.56 de	3.69 c-e	4.33 d-f	409.67 ab	392.33 a	115.00 b	93.67 cd
	CV (%)	5.84	4.32	7.95	7.02	1.78	1.74	3.24	3.88
	HSD	1.68	1.35	0.86	0.87	19.04	16.40	9.72	10.52

Means ascribed to similar lettering do not differ significantly from each other by Tukey's HSD test at (P< 0.05)

view of the biplot in Fig. 4A and Fig. 4B for the first and second production cycle that the majority of the traits are seemingly crowded around the sector where *Grand Naine* at 400 g plant^{-1} TSP rate represents the vertex coordinate, which signifies the TSP rate responsible for attaining the highest index in those traits. The presence of the other *Grand Naine*-P rate combinations in the same sector also implies the superiority of the performance of *Grand Naine* in these traits to other cultivar- P rate combinations which seem to be scattered on the right portion of the biplot. Only the plant height, days from planting to flower emergence and days from flower emergence to harvesting are dispersed in the opposite direction of those traits, indicating that they elicited a differential response pattern unlike those other bunch traits. The number of hands per bunch was significantly affected by the P fertilization rate and the cultivar. The highest magnitude of number of hands per bunch was obtained at 400 g plant^{-1} TSP rate for *Grand Naine* (13.62 and 13.84), *Champa* (9.50 and 10.45) and *Anupom* (8.12 and 8.78) in the first and second production cycle respectively although the differences in the magnitude among the control, 200, 300, 400 and the 500 g plant^{-1}TSP rate were trivial. The 400 g plant^{-1}TSP rate also exerted the highest index in the number of fingers per hand in *Grand Naine* (12.41 and 13.02), *Champa* (10.35 and 11.53) and *Anupom* (10.22 and 10.73) with

Table 3. Mean bunch trait values of three banana cultivars in two production cycles under five P rates (Continued)

Cultivar	TSP rate (gm plant^{-1})	Inflorescence length (cm)		Peduncle length (cm)		Bunch length (cm)		Fruit length (cm)		Fruit diameter (cm)	
		1st cycle	2nd cycle	1st cycle	2nd cycle	1st cycle	2nd cycle	1st cycle	2nd cycle	1st cycle	2nd cycle
Grand Naine	0	118.61 c	121.33 d	30.45 de	32.14 f	49.25 c	51.11 e	11.58 de	12.27 hi	150.64 d	155.27 e
	200	127.11 b	129.59 c	34.96 c	38.47 d	53.69 bc	57.29 d	14.32 c	16.66 d	162.25 c	167.73 d
	300	130.26 b	136.62 ab	39.11 b	42.18 b	57.21 ab	66.02 b	17.77 b	20.82 b	174.77 b	194.78 b
	400	136.20 a	140.41 a	44.09 a	47.75 a	61.45 a	70.37 a	19.45 a	22.43 a	185.13 a	220.37 a
	500	128.63 b	130.39 bc	36.27 c	40.41 c	56.19 b	62.86 c	16.89 b	18.72 c	164.65 c	177.70 c
Champa	0	74.17 g	77.32 gh	23.54 h	24.11 i	27.26 g-i	30.19 h	8.37 h	8.55 k	53.90 j	57.91 j
	200	79.26 f	83.55 f-h	26.33 fg	27.26 h	31.67 e-g	35.89 g	9.69 fg	9.47 k	63.32 i	67.60 i
	300	82.04 ef	90.35 ef	28.25 ef	32.17 f	35.51 e	42.16 f	11.54 de	12.58 gh	77.01 g	84.69 h
	400	90.32 d	97.04 e	31.56 d	36.45 e	40.79 d	50.37 e	12.73 d	13.59 fg	87.38 f	95.77 g
	500	80.62 ef	85.05 f	27.96 ef	29.02 g	34.12 ef	38.31 g	10.81 ef	11.05 j	69.64 h	71.38 i
Anupom	0	55.33 i	57.11 j	16.16 k	16.39 k	20.14 j	24.19 i	8.64 gh	9.01 k	63.19 l	67.60 i
	200	64.14 h	68.36 i	18.25 jk	21.14 j	26.23 hi	31.25 h	10.22 f	11.36 ij	77.77 g	79.23 h
	300	72.15 g	85.93 f	20.89 i	27.77 gh	29.84 f-h	37.83 g	12.50 d	14.63 ef	86.02 f	96.82 g
	400	82.87 e	84.19 fg	24.12 gh	31.23 f	33.78 ef	43.26 f	14.44 c	15.58 de	96.43 e	107.73 f
	500	63.78 h	76.81 h	18.78 ij	20.87 j	22.81 ij	30.36 h	10.80 ef	13.81 f	73.22 gh	85.70 h
	CV (%)	1.25	2.36	3.08		1.68		4.34	2.08	3.25	2.75
	HSD	3.48	6.97	2.61		1.59		5.07	2.81	5.76	6.59

Means followed by the same letter within a column do not differ significantly according to Tukey's HSD test at $P < 0.05$.

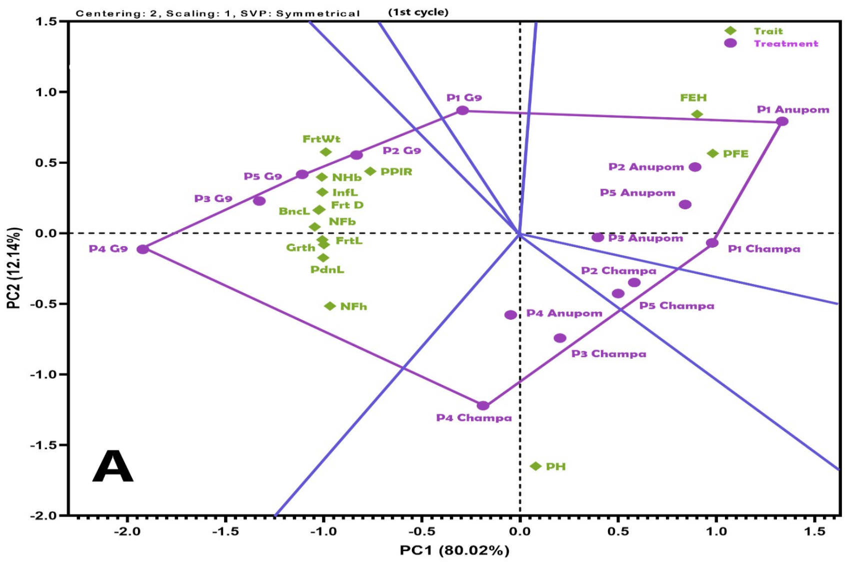

Figure 4A. Polygon view of the biplot showing the superiority of TSP @400 g plant^{-1} based on trait profile and response of different cultivar- P rate combination for first cycle. Here, P1= 0, P2= 200, P3= 300, P4= 400, P5= 500 g plant-1 TSP; V1= Grand Naine, V2= Champa, V3= Anupom; PH= plant height, Grth= girth, NHb= number of hand per bunch, NFh= number of finger per hand, NFb= number of finger per bunch, InfL= inflorescence length, PdnL= peduncle length, BncL= bunch length, FrtL= fruit length, FrtD= fruit diameter, FrtWt= fruit weight, PPlR= pulp-peel ratio, PFE= days from planting to flower emergence and FEH= days from flower emergence to harvesting. PC= Principal component.

little variation among the other P fertilization rates for the first and second production cycle, respectively. Significant variation was observed in the relative level of the number of fingers per bunch imposed by five different P fertilization rates for all of three cultivars. The 400 g plant^{-1} TSP rate led to the highest yield in this trait in *Grand Naine* (167.68 and 188.26), *Champa* (107.01 and 120.43) and *Anupom* (82.30 and 94.16) for the first and second production cycle respectively and it invoked 12.27%, 12.54% and 14.41% more yield in the second production cycle in comparison to the first one in *Grand Naine, Champa* and *Anupom*, respectively.

This result is justified by the findings of Al-Harthi Al-Yahyai (2009), Attia *et al.* (2009) and Butani *et al.* (2012) as they observed similar pattern of increase in these bunch attributes as a response to ascending P rate although their optimum P rate was little bit higher compared to our present investigation. For the inflorescence length, the maximum value was observed to achieve at 400 g plant^{-1} TSP rate in *Grand Naine* (136.20 cm), *Champa* (90.32cm) and *Anupom* (82.87cm) which were 3.09%, 7.44% and 1.59% higher in comparison to the second cycle. Although all of the three cultivars were appeared to be more responsive to the ascended P fertilization rate up to 400 g plant^{-1} P rate TSP rate in the second production cycle compared to the first one in terms of peduncle length and bunch length, the magnitude of the yield was higher in the *Grand Naine* than *Champa* and *Anupom*, evidenced from the Table 1. A prominent significant response was exhibited in the fruit characteristics as a result of differential P fertilization. The ascending TSP rate exerted a limited increase in the fruit length and fruit diameter in comparison to fruit weight in all three cultivars. The maximum magnitude was attained at 400 g plant^{-1} TSP rate, more conspicuous in *Grand Naine* (185.13 g and 220.37 g) rather than *Champa* (87.38 g and 95.77 g) and *Anupom* (96.43 g and 107.73 g) in terms of the fruit weight for the first and second production cycles respectively as become noteworthy from the Fig. 4A and Fig. 4B and the Table 1. The superiority ranking of the different treatment combination across all the traits, glimpsed from the *ATC view* of the biplot in Fig. 5A and Fig. 5B indicating the superiority of *Grand Naine* (P4V1>P3V1>P5V1>P2V1, placed on the left side of the *ATC ordinate*) over the *Champa* and the *Anupom* for above-average response to P fertilization across all traits except the phenological one (days from planting to flower emergence and days from flower emergence to harvesting) and plant height.

An interesting, noteworthy fact that can easily be evinced from the *ATC view* of the biplot (Fig. 5A and Fig. 5B) is that the downturn in magnitude in almost all traits at 500 g plant^{-1} P rate (P5) in all of the three cultivars which resembles the quadratic P response. This result is found to be in well congruence with the findings of Silva & Rodrigues (2013), Liu *et al.* (2015), Batista Bolfarini *et al.* (2016), Leonel *et al.* (2020b) and Bolfarini *et al.* (2020) as they observed similar kind of quadratic response to increasing P fertilization in various commercial hybrid Brazilian banana cultivars. The effect of P fertilization rate seemed to be less conspicuous in the trait of pulp-peel ratio although the ratio tended to be higher in the second production cycle in *Grand Naine* for the 400 g plant^{-1} TSP rate.

The impact of the P fertilization tended to be more pronounced in days from planting to flower emergence and days from flower emergence to harvesting in all three cultivars due to its placement at the farthest opposite corner apart from other traits in the biplot (Fig. 4A and Fig. 4B). The common pattern of response, envisaged from the Fig. 4A, Fig. 4B and the Table 1 was that the relative temporal interval between the planting and flower emergence and between the flower emergence and harvesting became shorter up to the 400 g plant^{-1} TSP rate, more vividly experienced in *Grand Naine* followed by *Champa* and *Anupom*. In comparison to the first cycle, the second cycle was observed with shorter duration for days from planting to flower emergence and days from flower emergence to harvesting in all of three cultivars, underpinned by the findings of Taulya *et al.* (2014) and Leonel *et al.* (2020b). For the trait of girth, the highest value was experienced in *Grand Naine* (70 cm and 77.75 cm) followed by the *Champa* (44.64

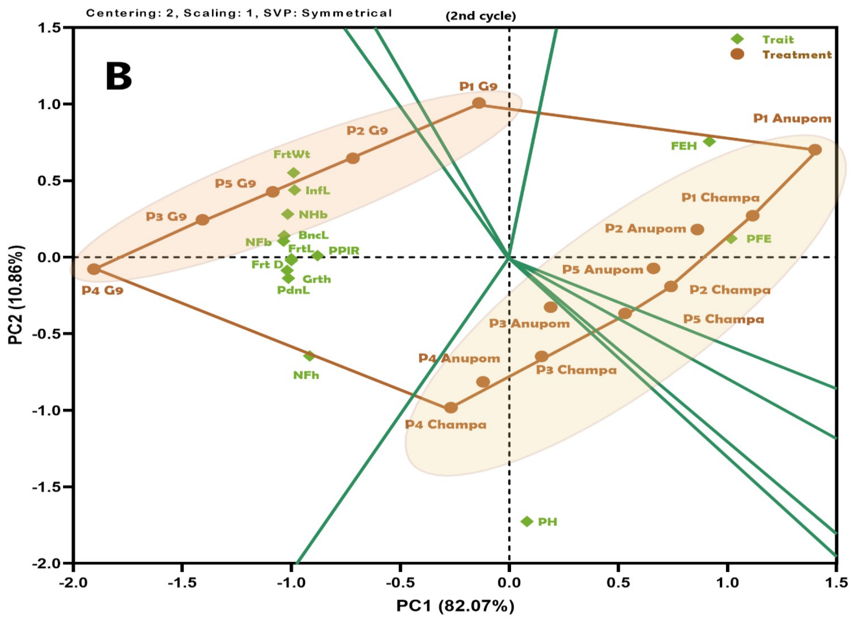

Figure 4B. Polygon view of the biplot showing the superiority of TSP @400 g plant-1 based on trait profile and response of different cultivar- P rate combination for second cycle. Here, P1= 0, P2= 200, P3= 300, P4= 400, P5= 500 g plant-1 TSP; V1= Grand Naine, V2= Champa, V3= Anupom; PH= plant height, Grth= girth, NHb= number of hand per bunch, NFh= number of finger per hand, NFb= number of finger per bunch, InfL= inflorescence length, PdnL= peduncle length, BncL= bunch length, FrtL= fruit length, FrtD= fruit diameter, FrtWt= fruit weight, PPlR= pulp-peel ratio, PFE= days from planting to flower emergence and FEH= days from flower emergence to harvesting. PC= Principal component.

cm and 51.49 cm) and the *Anupom* (40.83 cm and 47.89 cm), which appeared to occur for the 400 g plant^{-1} TSP rate in the first and second cycle, respectively. But the response invoked in plant height was contrary to the response exhibited in the other traits as it was positioned at the farthest corner of the biplot revealed in Fig.4A and Fig. 4B.

The maximum value was attained by *Champa* (303.75 cm and 312.83 cm) followed by the *Anupom* (250.35 cm and 274.59 cm) and the *Grand Naine* (190.52 cm and 198.12 cm) at 400 g plant^{-1} TSP rate for the first and second production cycle, respectively. This variable response pattern observed in plant height might be attributed to the variability in genotypic architecture of the different cultivars, which significantly affect the genetic potentiality as it is prominent that the *Champa* (AAB) and *Anupom* (AAB), belonging to Horn plantain subgroup outperformed the *Cavendish* subgroup cultivar, *Grand Naine* (AAA) in plant height in invoking response to augmented P fertilization (Lopes *et al.* 2020, Leonel *et al.* 2020a). Similar P fertilization mediated linear increase in plant height and the pseudo stem girth was observed in the Brazilian commercial hybrid *"FHIA 18"* and *"Prata ana"* banana cultivars (Guimarães *et al.* 2014, Leonel *et al.* 2020b). A common pattern can be characterized from the *polygon* (Fig. 4A and Fig. 4B) and the *ATC view* of the biplot (Fig. 5A and Fig. 5B) in which, majority of the traits continued constant increment in the magnitude up to the 400 g plant^{-1} TSP rate followed by an abrupt decrease at 500 g plant^{-1} TSP rate. Despite the presence of large amount of inorganic P in immobilized adsorbed mineral state, a very little concentration is readily available for plant uptake that introduces P deficiency in soil.

The higher pH, lower amount of organic matter, higher weathering of the mineral in tropical climate accelerates the P deficiency, which leads the farmer to the excessive P fertilization for ameliorating this deficiency. This excessive P readily undergoes pH mediated chemical

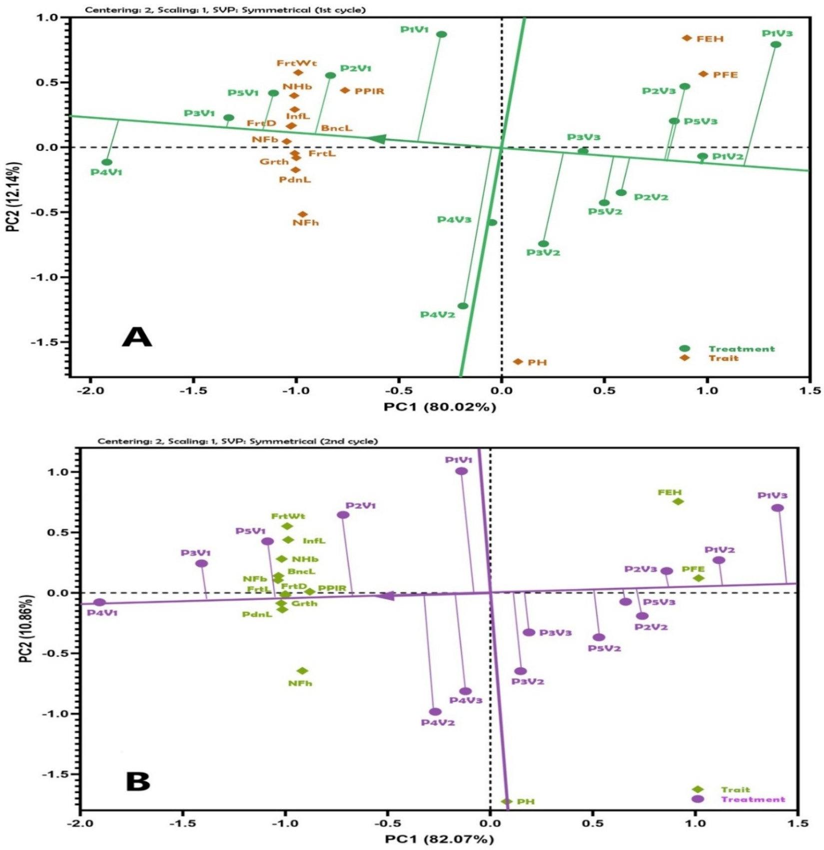

Figure 5. Average Trait Coordination (ATC) view of the biplot showing mean and consistency of the various cultivar-P rate combination in terms of trait response: (A) for first cycle and (B) for second cycle that depicts the superiority of the Grand Naine P response over the other two. Here, P1= 0, P2= 200, P3= 300, P4= 400, P5= 500 g plant-1 TSP; V1= Grand Naine, V2= Champa, V3= Anupom; PH= plant height, Grth= girth, NHb= number of hand per bunch, NFh= number of finger per hand, NFb= number of finger per bunch, InfL= inflorescence length, PdnL= peduncle length, BncL= bunch length, FrtL= fruit length, FrtD= fruit diameter, FrtWt= fruit weight, PPlR= pulp-peel ratio, PFE= days from planting to flower emergence and FEH= days from flower emergence to harvesting. PC= Principal component.

fixation with Fe and Al oxide producing insoluble solid complex that which renders the deficiency of P more acute (Schachtman *et al.* 1998, Rohily *et al.* 2013, Fallah Nosratabad *et al.* 2017). This P unavailability initiate "P induced Zn deficiency" in the plant along with reduction of root growth, which ultimately hinders the nutrient uptake and causes drastic yield dropping (Mustaffa & Kumar 2012, Bolan *et al.* 2015). Moreover, the excessive P and N application exerts a detrimental role in diminishing the phosphate solubilizing microbiome that acts as a key role player for increasing the P availability in soil (Sun *et al.* 2018, Zhu *et al.* 2018). Despite of this fact, the excessive P mediated photosynthesis reduction through hindering the ribulose 1,5-bisphosphate and fixation of CO_2 also might contribute to the growth reduction (Nord *et al.* 2011). Another discernible pattern, retrieved from the biplot and numerical Table was that the magnitude achieved in the majority of the traits by all three cultivars was higher in the second production cycle in comparison to the first one. This improvement can be attributed to the increased availability of residual P after annual P application along with deeper and densely distribution of the root system, which confer increased nutrient uptake potential (Borges *et al*. 2008, Nomura *et al*. 2013). It is crystal clear from the ATC view of the biplot that the cultivar Grand Naine outperformed the Champa and the Anupom in terms of the majority of the bunch attributes in response to ascending P fertilization rate for both production cycles.

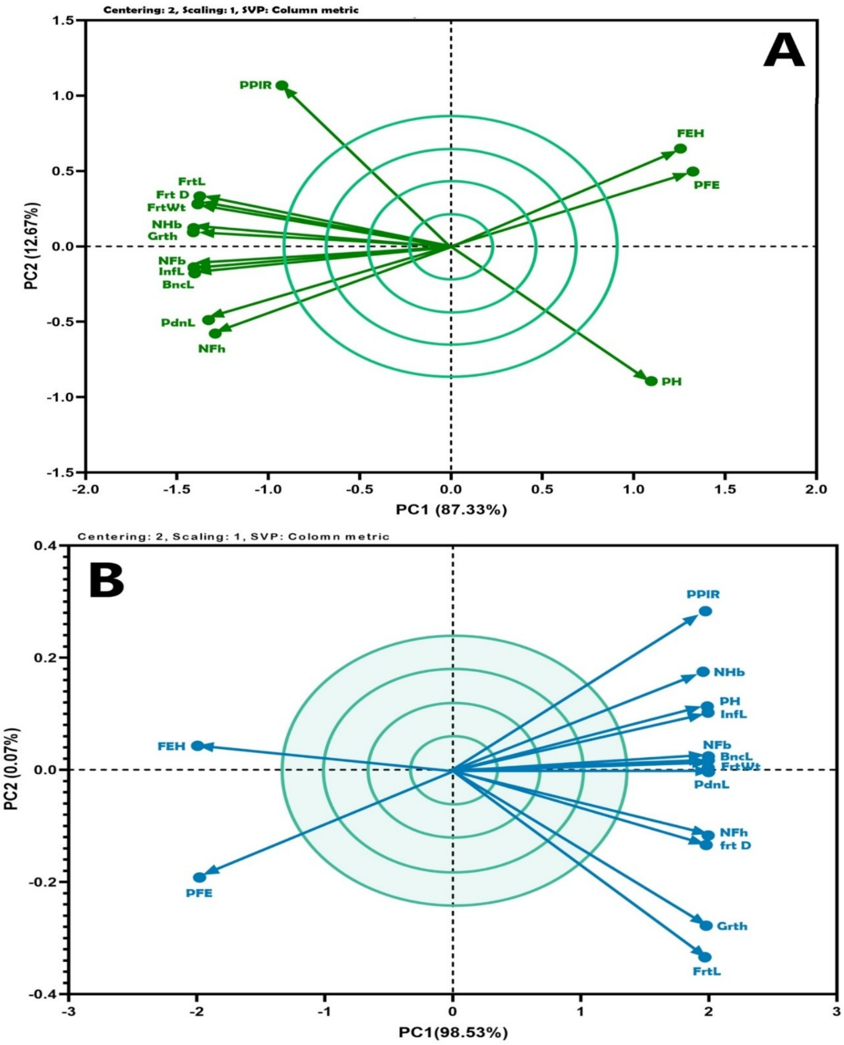

Figure 6. Vector view of the biplot showing the bunch trait relationship (A) across the cultivars and (B) across the P rates. Here, PH= plant height, Grth= girth, NHb= number of hand per bunch, NFh= number of finger per hand, NFb= number of finger per bunch, InfL= inflorescence length, PdnL= peduncle length, BncL= bunch length, FrtL= fruit length, FrtD= fruit diameter, FrtWt= fruit weight, PPlR= pulp-peel ratio, PFE= days from planting to flower emergence and FEH= days from flower emergence to harvesting. PC= Principal component.

Trait association between bunch morphology across the cultivars versus across the P rates

Incisive portraying of the trait relationship along with simultaneous depiction of their strength and weakness in the intuitive graphical interface is one of the core conveniences rendered by the vector view of the biplot as reflected in the Fig. (6A and 6B). The connecting lines between the biplot origin and the marker of the bunch and mineral traits are designated as “Trait Vector”. With large relative loadings and more than 90% of the variation explained by two PCs, the cosine angle between two trait vectors approximates the correlation coefficient between those two traits, whereas the angle depicts the positive (acute angle) or negative (obtuse angle) correlation and the length measures the strength and weakness of the relation (Yan Kang 2002). Vector view of the biplot manifested in Fig. 6A reflects the genetic relationship among the attributes across the all three cultivars irrespective of the effect of P fertilization rate. It is clearly perceivable from exploring the relationship pattern that due to the dense and crowded position of bunch trait points in a particular side of the biplot, strong positive correlation is prevalent between them for bearing an acute angle between their trait vectors. The obtuse angle between these groups of bunch characteristics and days from planting to flower emergence, days from flower emergence to harvesting or plant height vectors

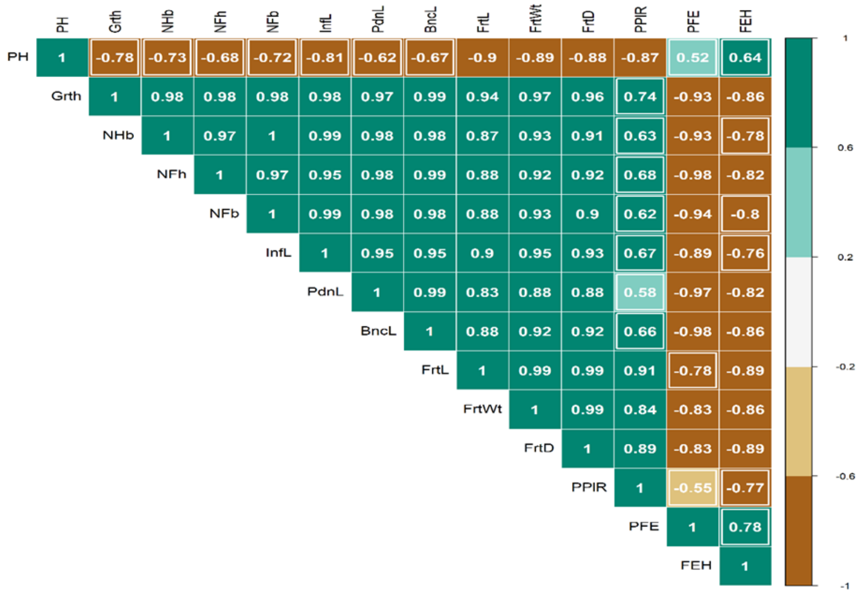

Figure 7. (A) Showing the correlation coefficient among the bunch traits across all banana cultivars. The enclosed white square indicates the insignificant correlation at 5% probability. Here, PH= plant height, Grth= girth, NHb= number of hand per bunch, NFh= number of finger per hand, NFb= number of finger per bunch, InfL= inflorescence length, PdnL= peduncle length, BncL= bunch length, FrtL= fruit length, FrtD= fruit diameter, FrtWt= fruit weight, PPlR= pulp-peel ratio, PFE= days from planting to flower emergence and FEH= days from flower emergence to harvesting.

reflects the existing negative association among them.

The most prominent relationships were a) the significant near perfect positive association among number of hand per bunch, number of finger per hand, number of finger per bunch, bunch length and the inflorescence length, b) the perfect positive significant association among fruit weight, fruit length and fruit diameter c) the negative strong significant relationship between fruit yield (fruit length, diameter and weight) parameters and phenological attributes (days from planting to flower emergence and days from flower emergence to harvesting), d) the strong negative association between plant height and fruit yield parameters (fruit length, diameter and weight). Although not usual, but significant strong relationships in bunch attributes and fruit yield attributes implicates that the higher magnitude in the number of fingers per hand or number of fingers per bunch likely led to a higher index in the fruit size and weight parameters, considered a desirable trait combination. The negative significant association between phenological traits (days from planting to flower emergence and days from flower emergence to harvesting) and fruit yield attributes also standout as desirable association as the shorter temporal span of phenological traits (days from planting to flower emergence and days from flower emergence to harvesting) were tended to be accompanied with higher magnitude in fruit length, diameter and weight. A similar relationship pattern was observed by Guimarães *et al.* (2014), Bolfarini *et al.* (2020) and Leonel *et al.* (2020a) in bunch attributes underpins the current findings. The strong significant negative association between plant height and fruit yield attributes also denoted desirable trait association as the higher fruit yield (fruit length, diameter and weight) tended to appear with shorter plant height. All of these trait relations can be considered as favorable associations for a promising breeding platform focused on combining desirable trait packages in cultivar development (Bolfarini *et al.* 2020, Leonel *et al.* 2020a).

The vector view of the biplot in Fig. 6B portraying the bunch trait association across the all-TSP rates represents the almost similar

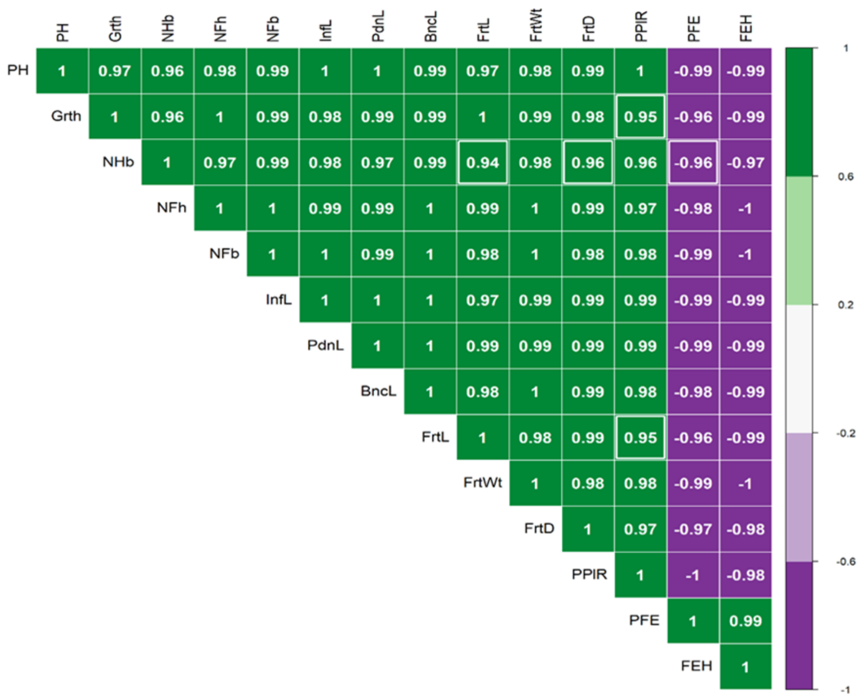

Figure 8. Correlation coefficient among the bunch traits across all P rates. The enclosed white square indicates the insignificant correlation at 5% probability. Here, PH= plant height, Grth= girth, NHb= number of hand per bunch, NFh= number of finger per hand, NFb= number of finger per bunch, InfL= inflorescence length, PdnL= peduncle length, BncL= bunch length, FrtL= fruit length, FrtD= fruit diameter, FrtWt= fruit weight, PPlR= pulp-peel ratio, PFE= days from planting to flower emergence and FEH= days from flower emergence to harvesting.

pattern of bunch trait association that reflected in the trait relationship across the cultivars in Fig. 6A. But the bunch trait association across the cultivar in Fig. 6A renders slightly different insight in comparison to the trait association across the P rate as evinced in the Fig. 6B. The contrasting difference arouse from the association regarding plant height as the plant height was found to be in significant strong positive association with other bunch attributes in the trait association across TSP rate in Fig. 6B. This particular association rather highlights the undesirable trait linkage for rendering difficulties in harvesting operation from higher height and it may possess constant challenge in attaining desirable trait package for desirable cultivar development. This phenomenon infers nothing but the discrepancies that exist between the genetic correlation and the environmental correlation between the yield and quality traits (Yan *et al*. 2017). All of these trait relationships as evinced from the vector view of the biplot are in well corroboration with numerical correlation data manifested in the Fig.7 and Fig. 8.

CONCLUSIONS

The investigation devoted to scrutinize the effect of differential P fertilization rate on the bunch morphology and fruit yield parameters of three banana cultivars led us to discern following inference, first, all of the three cultivars *Grand Naine, Champa* and *Anupom* exhibited consistent increment in the magnitude of all bunch attributes and experienced shorter phenological cycle (days from planting to flower emergence and days from flower emergence to harvesting) as a response to the ascending P fertilization which culminating in 400 g plant^{-1} TSP rate. Second, the responsiveness to P fertilization was more conspicuous in the cultivar *Grand Naine* in comparison to the *Champa* and the *Anupom* as revealed by more pronounced enhancement in bunch morphological attributes due to its superior genetic architecture. Third, a longer phenological cycle and a drastic decline in the level of all bunch and yield parameters were experienced by all of the three cultivars at 500 g plant^{-1} TSP rate signified the detrimental effect of excessive Phosphate fertilization. And finally, all three cultivars showed prominent productivity in all of the bunch traits in the second production cycle compared to the first one. So, 400 g plant^{-1} TSP or 80 g plant^{-1} TSP rate appears to be appropriate for augmenting the productivity of banana and reducing the excessive P fertilization mediated soil toxicity.

REFERENCES

Al-Harthi K, Al-Yahyai R (2009) Effect of NPK fertilizer on growth and yield of banana in Northern Oman. *Journal of Horticulture and Forestry*, 1, 160–167.

Attia M, Ahmed M, El-Sonbaty M (2009) Use of biotechnologies to increase growth, productivity and fruit quality of Maghrabi banana under different rates of phosphorus. *World Journal of Agricultural Sciences*, 5(2), 211–220.

Batista Bolfarini AC, Leonel S, Leonel M, Tecchio MA, de Souza Silva M, Azevedo Souza JM (2016) Growth, yield and fruit quality of “maçã” banana under different rates of phosphorus fertilization. *Australian Journal of Crop Science*, 10(9), 1368–1374. https://doi.org/10.21475/AJCS.2016.10.09.P7892.

Bhalerao VP, Patil NM, Badgujar CD, Patil DR (2009) Studies on integrated nutrient management for tissue cultured Grand Naine banana. *Indian Journal of Agricultural Research*, 43, 107–112.

Bolan NS, Adriano DC, Naidu R, De La Luz Mora M, Santiagio M (2015) Phosphorus-Trace Element Interactions in Soil-Plant Systems. In: *Phosphorus: Agriculture and the Environment*, Vol 46. (Sims T and Sharpley AN Eds.). John Wiley & Sons, Ltd, ASA, CSA, SSSA, Madison, WI. 317–352. https://doi.org/10.2134/AGRONMONOGR46.C10.

Bolfarini ACB, Putti FF, Souza JMA, Silva M de S, Ferreira RB, Leonel M, Tecchio MA, Leonel S (2020) Application of phosphate fertilization on banana hybrid ‘FHIA 18’ and its impact on production performance. *Australian Journal of Crop Science*, 14(5), 744–750. https://doi.org/10.21475/AJCS.20.14.05.P2081.

Borges AL, Souza LDS, Peixoto CAB, Dos Santos JLC (2008) Distribution of the “prata anã” root system in two urea fertirrigation frequencies. *Revista Brasileira de Fruticultura*, 30(1), 259–262.https://doi.org/10.1590/S0100-29452008000100048.

Borges CV, Maraschin M, Coelho DS, Leonel M, Gomez HAG, Belin MAF, Diamante MS, Amorim EP, Gianeti T, Castro GR, Lima GPP (2020) Nutritional value and antioxidant compounds during the ripening and after domestic cooking of bananas and plantains. *Food Research International*, 132, 109061. https://doi.org/10.1016/J.FOODRES.2020.109061.

Butani AM, Chovatia RS, Patel K, Vadaria KN, Rankja NJ (2012) Effect of chemical fertilizer and vermicompost on yield and nutrient content and uptake by fruit of banana (Musa parasidiaca L.) cv. GRAND NAINE. *The Asian Journal of Horticulture*, 7, 594–598.

Cai H, Xie W, Lian X (2013) Comparative Analysis of Differentially Expressed Genes in Rice Under Nitrogen and Phosphorus Starvation Stress Conditions. *Plant Molecular Biology Reporter*, 31(1), 160–173. https://doi.org/10.1007/S11105-012-0485-8/FIGURES/5.

Choudhury N, Nickhil C, Deka SC (2023) Comprehensive review on the nutritional and therapeutic value of banana by-products and their applications in food and non-food sectors. *Food Bioscience*, 56, 103416. https://doi.org/10.1016/J.FBIO.2023.103416.

Fallah Nosratabad AR, Etesami H, Shariati S (2017) Integrated use of organic fertilizer and bacterial inoculant improves phosphorus use efficiency in wheat (Triticum aestivum L.) fertilized with triple superphosphate. *Rhizosphere*, 3, 109–111. https://doi.org/10.1016/j.rhisph.2017.03.001.

FAOSTAT (2024) Food and Agriculture Organization of the United Nations. Available from: https://www.fao.org/faostat/en/data/QCL (March 28, 2024).

Frutos E, Galindo MP, Leiva V (2014) An interactive biplot implementation in R for modeling genotype-by-environment interaction. *Stochastic Environmental Research and Risk Assessment*, 28(7), 1629–1641. https://doi.org/10.1007/s00477-013-0821-z.

Fuller DQ, Madella M (2009) Banana Cultivation in South Asia and East Asia: A review of the evidence from archaeology and linguistics. *Ethnobotany Research and Applications*, 7, 333–351.

Guimarães BVC, Donato SLR, Maia VM, Aspiazú I, Coelho EF (2014) Phenotypical correlations between agronomical characters in Prata type bananas (Musa) and its implications on yield estimate. *African Journal of Agricultural Research*, 9(17), 1358–1365. https://doi.org/10.5897/AJAR12.2140.

Huq SMI, Shoaib JUMd (2013) Soil Classification. In: *The Soils of Bangladesh*. (Huq SMI and Shoaib JUMd Eds.). Springer Netherlands, Dordrecht. 71–82.https://doi.org/10.1007/978-94-007-1128-0_8.

Leonel M, Bolfarini ACB, Rodrigues da Silva MJ, Souza JMA, Leonel S (2020a) Banana fruits with high content of resistant starch: Effect of genotypes and phosphorus fertilization. *International Journal of Biological Macromolecules*, 150, 1020–1026. https://doi.org/10.1016/J.IJBIOMAC.2019.10.217.

Leonel S, Bolfarini ACB, Souza JMA, Leonel M, Ferreira RB, Putti FF, Tecchio MA (2020b) Agronomic performance of Banana ‘FHIA 18’ in response to phosphate fertilization. *Agronomy Journal*, 112(3), 2033–2046. https://doi.org/10.1002/AGJ2.20166.

Liu Y, Jing T, Tang F, Zang X, Zheng W, Cao H, Ju J, Wang B, Li C (2015) Studies on the Fertilization Effect and Optimal Fertilizing Amount of Brazil Banana Based on “3414” Field Trials. *Journal of Agricultural Science & Technology*, (9), 1950–1954.

Lopes S, Borges CV, de Sousa Cardoso SM, de Almeida Pereira da Rocha MF, Maraschin M (2020) Banana (Musa spp.) as a Source of Bioactive Compounds for Health Promotion. In: *Handbook of Banana Production, Postharvest Science, Processing Technology, and Nutrition*. John Wiley & Sons, Ltd. 227–244. https://doi.org/10.1002/9781119528265.ch12.

Mohd Zaini H, Roslan J, Saallah S, Munsu E, Sulaiman NS, Pindi W (2022) Banana peels as a bioactive ingredient and its potential application in the food industry. *Journal of Functional Foods*, 92, 105054. https://doi.org/10.1016/J.JFF.2022.105054.

Mukul AZA, Rahman MA (2013) Production and Profitability of Banana in Bangladesh-An Economic Analysis. *International Journal of Economics, Finance and Management Sciences*, 1(3), 159–165. https://doi.org/10.11648/j.ijefm.20130103.15.

Mustaffa MM, Kumar V (2012) Banana Production and Productivity Enhancement through Spatial, Water and Nutrient Management. *Journal of Horticultural Sciences*, 7(1), 1–28. https://doi.org/10.24154/jhs.v7i1.383.

Nomura ES, Moraes WS, Damatto Junior ER, Fuzitani EJ, Saes LA, Amorim EP, Silva SO (2013) Evaluation of banana genotypes over two crop cycles under subtropical conditions in the Ribeira Valley São Paulo Brazil. *Acta Horticulturae*, 986, 61–70. https://doi.org/10.17660/ACTAHORTIC.2013.986.4.

Nord EA, Shea K, Lynch JP (2011) Optimizing reproductive phenology in a two-resource world: A dynamic allocation model of plant growth predicts later reproduction in phosphorus-limited plants. *Annals of Botany*, 108(2), 391–404. https://doi.org/10.1093/AOB/MCR143.

Ova EA, Kutman UB, Ozturk L, Cakmak I (2015) High phosphorus supply reduced zinc concentration of wheat in native soil but not in autoclaved soil or nutrient solution. *Plant and Soil*, 393(1–2), 147–162. https://doi.org/10.1007/S11104-015-2483-8.

Qamar S, Shaikh A (2018) Therapeutic potentials and compositional changes of valuable compounds from banana- A review. *Trends in Food Science & Technology*, 79, 1–9. https://doi.org/10.1016/J.TIFS.2018.06.016.

R Core Team (2024) R: A Language and Environment for Statistical Computing. Available from: https://www.R-project.org.

Rohily KM, Ghoneim A, Modaihsh A, Mahjoub M (2013) Phosphorus Availability in Calcareous Soil Amend with Chemical Phosphorus Fertilizer, Cattle Manure Compost and Sludge Manure. *International Journal of Soil Science*, 8(1), 17–24. https://doi.org/10.3923/ijss.2013.17.24.

Schachtman DP, Reid RJ, Ayling SM (1998) Phosphorus Uptake by Plants: From Soil to Cell. *Plant Physiology*, 116(2), 447–453. https://doi.org/10.1104/PP.116.2.447.

Shen J, Yuan L, Zhang J, Li H, Bai Z, Chen X, Zhang W, Zhang F (2011) Phosphorus dynamics: From soil to plant. *Plant Physiology*, 156(3), 997–1005. https://doi.org/10.1104/PP.111.175232.

Silva JTA da, Rodrigues MGV (2013) Production of 'Prata Anã' banana as affected by the application of phosphate fertilizer, in four cycles. (In Portuguese with English abstract). *Pesquisa Agropecuaria Brasileira*, 48(6), 613–618. https://doi.org/10.1590/S0100-204X2013000600006.

Sun J, Zou L, Li W, Yang J, Wang Y, Xia Q, Peng M (2018) Rhizosphere soil properties and banana Fusarium wilt suppression influenced by combined chemical and organic fertilizations. *Agriculture, Ecosystems & Environment*, 254, 60–68. https://doi.org/10.1016/J.AGEE.2017.10.010.

Taulya G, van Asten PJA, Leffelaar PA, Giller KE (2014) Phenological development of East African highland banana involves trade-offs between physiological age and chronological age. *European Journal of Agronomy*, 60, 41–53. https://doi.org/10.1016/J.EJA.2014.07.006.

Yan W, Rajcan I (2002) Biplot analysis of test sites and trait relations of soybean in Ontario. *Crop Science*, 42(1), 11–20. https://doi.org/10.2135/cropsci2002.1100.

Yan W, Kang MS (2002) *GGE Biplot Analysis: A Graphical Tool for Breeders, Geneticists, and Agronomists*. CRC Press, Boca Raton. 288 p. https://doi.org/10.1201/9781420040371.

Yan W, Fregeau-Reid J, Ma BL, Pageau D, Vera C (2017) Nitrogen fertilizer complements breeding in improving yield and quality of milling oat. *Crop Science*, 57(6), 3291–3302. https://doi.org/10.2135/cropsci2017.05.0290.

Zhang Z, Liao H, Lucas WJ (2014) Molecular mechanisms underlying phosphate sensing, signaling, and adaptation in plants. *Journal of Integrative Plant Biology*, 56(3), 192–220. https://doi.org/10.1111/JIPB.12163.

Zhao Z, Shi H juan, Wang M lin, Cui L, Zhao H, Zhao Y (2015) Effect of nitrogen and phosphorus deficiency on transcriptional regulation of genes encoding key enzymes of starch metabolism in duckweed (Landoltia punctata). *Plant Physiology and Biochemistry*, 86, 72–81. https://doi.org/10.1016/J.PLAPHY.2014.11.007.

Zhu J, Li M, Whelan M (2018) Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: A review. *Science of The Total Environment*, 612, 522–537. https://doi.org/10.1016/J.SCITOTENV.2017.08.095.