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Evaluation of Different Planting Dates on the Yield and Physio-Morphic Traits of Bambara Groundnut (*Vigna Subterranea L. Verdc*) Under Semi-Arid Climate of Pakistan.

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Abstract:

The agriculture sector must introduce new crops with high nutrition and adaptability to climate change in order to meet food insecurity under the threat of increasing population. Therefore, we examined the adaptability and yield of the Bambara groundnut under varying climatic conditions to optimize site-specific production technology. This study was conducted over the course of two years (2018, 2019) using a randomized complete block design (RCBD) where the treatments were replicated three times. The Bambara groundnut was sowed in three sowing dates (1st March, 1st April, and 1st May) at two locations (NARC, Koont) and yield and other traits were measured on this variety. The results showed that the date of planting (1st April) had a significant impact on the studied traits at each of the locations. Similarly, the crop's morphological and yield attributes exhibited a large amount of diversity. During 2018 and 2019, the NARC recorded biological yields of 10021–10013 (kg ha^{-1}) and seed yield of 2041–1973 (kg ha^{-1}) in 1st April compared to other sowing dates. Similarly, at Koont, pooled data from both years showed promising results of biological yield of 10056–10009 (kg ha^{-1}) and seed yield of 1974–1979 (kg ha^{-1}), respectively. The PCA analysis showed evidence of the excellency of 1st April over other sowing dates. It would appear that a significant adaptation of Bambara Groundnut was successfully accomplished in 1st April during both environments.

Keywords: Bambara groundnut, Food insecurity, Sowing dates, Physiology, Site optimization, Adaptability

1. Introduction

Pakistan faces significant food insecurity, with 20.3% of the population being malnourished or lacking access to food (Power et al., 2018). According to research by Hameed et al. (2020); Mahmood et al. (2023), around 40 million people, or 20.3% of the

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population, are stunted, underweight, wasted, or overweight. Children aged 6-59 months also face high malnutrition rates, with 40% being stunted, 28% underweight, 18% wasted, and 10% overweight (Cheema et al., 2022). Leguminous crops are a cheaper source of dietary protein and play a crucial role in agricultural ecosystems by fixing nitrogen symbiotically (Popolzuhina et al., 2021). Legumes are gaining popularity as a cheaper alternative to animal protein due to their widespread availability and potential protein content (Kazydub et al., 2020). Leguminous crops comprise around 12–15% of cultivable land, account for 27% of total crop output, and provide 33% of the worldwide daily protein requirements of the human body.. However, Pakistan's pulses production is only 5% of the total cropped area, with a 12% decrease from 1.24 Mt (Bhagat et al., 2024). Factors contributing to this include lack of crop improvement and seed distribution systems, biotic and abiotic stresses, and soil issues like marginal soils. Pakistan is now undertaking breeding initiatives aimed at enhancing the productivity of leguminous crops, with a specific emphasis on enhancing their drought resilience, disease tolerance, and adaptation to the local environment (Maqbool et al., 2017; Pataczek et al., 2018; A. Ullah et al., 2020). Farmers and researchers develop hybrids and cultivars to boost yield and nutritional quality in Pakistan's leguminous crops, aligning agricultural techniques and production.

In Pakistan, the indigenous African bean known as Bambara groundnut gives a compelling opportunity for a wider range of agricultural practices. However, it is an exceptionally abundant protein as well as carbohydrates and fat source, which holds much promise in addressing the problem of protein deficiency (Oladimeji & Adebo, 2024). The seeds of this plant have a high nutrient content, ranging from 18 to 24% protein, between 6.0 and 6.5% fat, between 60.0 and 63% carbs, and 7.3% moisture (Olanrewaju et al., 2022). Bambara groundnuts are grown for human consumption, cattle feed, and medicinal purposes in Ibos culture, particularly for anti-vomiting medication (Mateva et al., 2023). Bambara groundnut is an adaptable plant, thriving in hot, dry weather and nutrient-deficient soils, unlike other crops like groundnut, sorghum, and maize. Farmers typically plant this crop in sandy soils since these soils have a high infiltration rate but low soil fertility. Bambara groundnut, despite its nutritional and economic value, is underexplored and under-researched due to the fact that global research on the crop remains limited (Mateva et al., 2023). Despite potential yields of over 3 t ha^{-1}, the current yield is 0.85 t ha^{-1} (Majola et al., 2021). Although a great deal of research work and concentrated efforts are needed on production technology and promotion of legume crops in Pakistan in order to meet their requirements. Furthermore, some efforts should be made to introduce new crops that have the potential to address malnutrition and food crisis. Keeping all above facts in view the present study was designed to evaluate adaptability, physio-morphic characteristics and yield of Bambara groundnut (*Vigna subterranean* L.) with the following objectives; determining the adaptability of

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Bambara on different sowing dates and location under semi-arid environments. The hypothesis of this study was that the Bambara groundnut could cover the yield gap of pulses and to meet the nutritional requirement of pulses in Pakistan.

2. Materials and Methods

2.1. Experimental Location Description

This standard field experiment was organized during growing seasons in 2018 and 2019 to evaluate the adaptability of Bambara groundnut at two different experimental locations of semi-arid climates. The first experimental location was National Agriculture Research Centre (NARC) Islamabad located at latitude: 33°67′21″ N, longitude: 73°12′52″ E with average annual rainfall of 1100-1400 mm. The second location was University Research Farm (URF) Koont, the experimental area of PMAS-Arid Agriculture University Rawalpindi having latitude: 33°11′01″ N, longitude: 73°01′64″ E with annual rainfall 500 to 1000 mm. The meteorological data for both locations was collected from Pakistan meteorology department (PMD) and presented in (Figure 1). The initial soil samples were also taken from each location and analyzed for physical and chemical characteristics as mentioned in Table 1.

Table 1. Initial physio-chemical properties of soil

Parameters	Unit	NARC		Koont	
		2018	2019	2018	2019
Texture	-	Sandy clay loam	Sandy clay loam	Sandy clay loam	Sandy clay loam
pH	-	7.84	7.81	7.61	7.59
Ec	ds m^{-1}	0.61	0.58	0.81	0.79
O.M	(%)	0.75	0.72	1.07	1.02
Porosity	(%)	42.3	41.5	47.5	47.2
B.D	g cm^{-3}	1.53	1.55	1.39	1.4
Mineral N	kg ha^{-1}	7.3	6.29	7.61	5.37
PAP	kg ha^{-1}	3.79	3.74	4.13	4.09
PAK	kg ha^{-1}	126	120	118	117

O.M: organic matter; B.D: bulk density; Mineral N: Mineral nitrogen; PAP: Plant available phosphorus in soil; PAK: Plant available potassium in soil.

2.1.1. Experimental Layout

This experiment was designed in randomized complete block design (RCBD) with three replications. To check best sowing date on one Bambara groundnut, the red variety was planted with three different sowing dates viz. 1st March, 1st April and 1st May. The size of each plot was 9 m^2 (1.8 m length × 5 m width). The crop was planted with single row hand drill with seeding depth 2.5-3 cm. Seed rate 50 kg ha^{-1} with rows distance 45cm and plants

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distance 15cm were kept after thinning. All agronomic practices were done to each experimental unit throughout the experiment.

2.1.2. Data collection

2.1.3. Relative Water Content (%)

The relative water content of the plant's fully expanded leaves was recorded for each treatment (Barrs & Weatherley, 1962). Prior to flowering, measurements were taken. Five plants were chosen from each allotment, and five leaves were harvested from each plant. After recording the fresh weight of the leaves, whole leaves were suspended in distilled water for 48 hours at room temperature. After drying the leaves with blotting paper for 24 hours at 70°C, the turgid weight of the foliage was determined. The following formula was used to calculate RWC;

$$RWC = \frac{(Fresh\ Leaf\ Weight - Dry\ Leaf\ Weight)}{Water\ Soaked\ Leaf\ weight} \times 100$$

Table 2. Meteorological data of both locations during 2018 and 2019.

			2018			
Month	**Minimum Temp ºC**	**Maximum Temp ºC**	**Rainfall mm**	**Minimum Temp ºC**	**Maximum Temp ºC**	**Rainfall mm**
January	2.0	19.2	1.0	2.5	15.1	141.3
February	5.6	20.4	78.0	5.8	15.9	126.1
March	11.3	26.8	39.6	8.6	21.3	74.2
April	15.0	31.5	85.0	15.3	30.6	91.0
May	18.7	34.8	65.0	16.6	34.5	52.0
June	23.8	38.0	63.0	20.3	39.2	31.0
July	24.1	34.4	373.6	22.8	35.4	252.4
August	24.1	34.8	532.5	22.5	33.5	535.5
September	21.4	33.7	105.0	20.3	33.1	97.6
October	13.0	29.2	31.0	12.3	29.2	42.2
November	7.7	24.2	24.0	10.0	21.6	54.6
December	2.5	18.3	30.4	2.5	17.3	16.0
				2019		
Month	**Minimum Temp ºC**	**Maximum Temp ºC**	**Rainfall mm**	**Minimum Temp ºC**	**Maximum Temp ºC**	**Rainfall mm**
January	4.2	19.2	0.6	3.6	15.1	39.7

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February	7.0	20.4	24.4	5.5	15.9	65.0
March	12.3	26.8	21.4	9.5	21.3	39.1
April	17.2	31.5	54.9	16.2	30.6	93.0
May	20.5	34.8	77.5	18.8	34.5	26.2
June	25.6	38.0	50.2	23.2	39.2	2.2
July	24.3	34.4	190.7	24.1	35.4	109.5
August	24.8	34.8	50.1	23.5	33.5	178.0
September	21.8	33.7	89.2	22.9	33.1	96.9
October	15.5	29.2	34.4	16.3	29.2	16.8
November	10.0	24.2	0.6	10.5	21.6	34.7
December	4.8	18.3	18.1	3.2	17.3	16.7

2.1.4. Estimation of physiological parameters

Stomatal conductance gs (mmol H_2O m^{-2} s^{-1}), photosynthetic active radiation PAR (mmol CO_2 mol^{-1} H_2O), net photosynthetic rate pn (µmol CO_2 m^{-2} s^{-1}) and transpiration rate (m mol m^{-2} s^{-1}) were measured by portable infrared gas analysis (IRGA model, LC-4, ADC Bio Scientific Ltd, Herts, England) at flower initiation stage.

2.1.5. Plant Morphological and Yield Parameters

Plant height was measured from the soil level to the tip of ten randomly selected plants from each plot at maturity using a meter rod, and the average was calculated. Days to maturity were calculated from the date of the initial plant's germination to the date when 75% of the crop changed color and became dry in each treatment. At maturity, the number of branches was counted on 10 randomly selected plants from each treatment, and an average was determined. The number of pods was counted from ten randomly selected plants from each treatment (not treatment its plot) at the time of harvest, and their average was taken. One hundred pods were randomly taken from each plot at maturity. The number of seeds were counted, for average seed per capsule. After threshing, three lots of hundred seeds were chosen from each treatment's (plot) bulk seed sample; the weight was taken with an electrical balance, and the average was calculated. Plants were dried in the sun for a few days after being picked in two meter long middle rows. The dried samples were weighed and converted to kilograms per hectare. (After sun drying, harvested plants from two-meter row lengths of two middle rows in each plot were threshed manually.

2.1.6. Seed Quality Parameters

The oil content of the seed was measured using an n-hexane solvent extraction approach while the protein content was measured via Kjeldahl approach (Elleuch et al., 2007).

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2.2. Statistical analysis

The collected data was subjected to MS-excel and analyzed by using SPSS software. The one way RCBD ANOVA applied and significant/non-significant were examined by using LSD test. The correlation and PCA were done through R programming software.

3. Results

3.1. Effect of different sowing dates on stomatal conductance (gs) of Bambara Groundnut

During both years, results showed that stomatal conductance gs (mmol H_2O m^{-2} s^{-1}) increased with different sowing dates at both locations (Figure 1). At NARC, gs was significantly higher by 190 mmol H_2O m^{-2} s^{-1} (2018), while it showed non-significant 181 mmol H_2O m^{-2} s^{-1} (2019) in 1st April than other sowing dates. Variations in results showed that it was 139-143 mmol H_2O m^{-2} s^{-1} (2018) and 143-155 mmol H_2O m^{-2} s^{-1} (2019) on 1st March and 1st May, but it was statistically non-significant. Similar results were obtained from Koont. It was observed that gs was significantly higher 179 mmol H_2O m^{-2} s^{-1} (2018) in 1st April. Remarkably, gs was increased 183 mmol H_2O m^{-2} s^{-1} (2019) in 1st April, while it was 152-144 mmol H_2O m^{-2} s^{-1} (2018) and 134-155 mmol H_2O m^{-2} s^{-1} (2019) in 1st March and 1st May respectively; however, it was statistically non-significant. Overall, 1st April showed best results in stomatal conductance followed by 1st May.

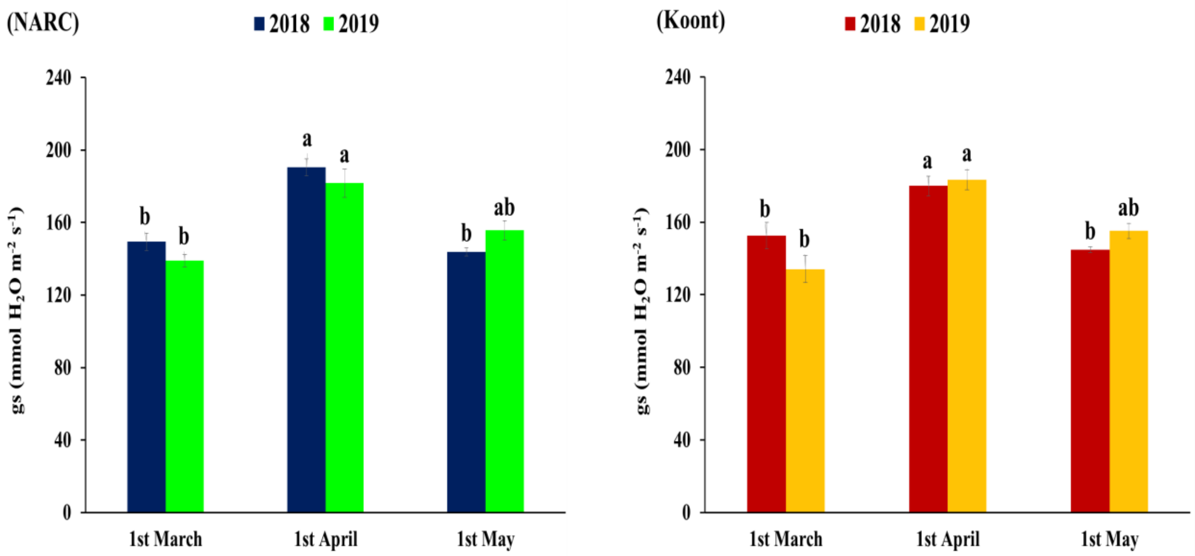

Figure 1. Effect of different sowing dates and locations on stomatal conductance gs (mmol H2O m^{-2} s^{-1}) of Bambara groundnut under rainfed conditions.

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3.2. Effect of different sowing dates on photosynthetic active radiation (PAR) of Bambara Groundnut

At NARC, photosynthetic active radiation (PAR) was 1011.66 µmol m^2 s^{-1} (2018) and 1017.32 µmol m^2 s^{-1} (2019) in 1st April (Figure 2). However, PAR was significantly higher 1123 µmol m^2 s^{-1} (2018) and 1162.65 µmol m^2 s^{-1} (2019) in 1st May than other sowing dates respectively. Furthermore, PAR was significantly lower 827.50 µmol m^2 s^{-1} (2018) and 809.84 µmol m^2 s^{-1} (2019) in 1st March. At Koont, PAR was 1004.12 µmol m^2 s^{-1} (2018) and 1047.45 µmol m^2 s^{-1} (2019) by crop sown in 1st April. Remarkably, PAR was significantly maximum 1162.40 µmol m^2 s^{-1} (2018) and 1200.86 µmol m^2 s^{-1} (2019) in 1st May, while it was minimum 870.42 µmol m^2 s^{-1} (2018) and 858.30 µmol m^2 s^{-1} (2019) in 1st March as compared to other sowing dates. However, PAR was optimum in 1st April compared to other sowing dates.

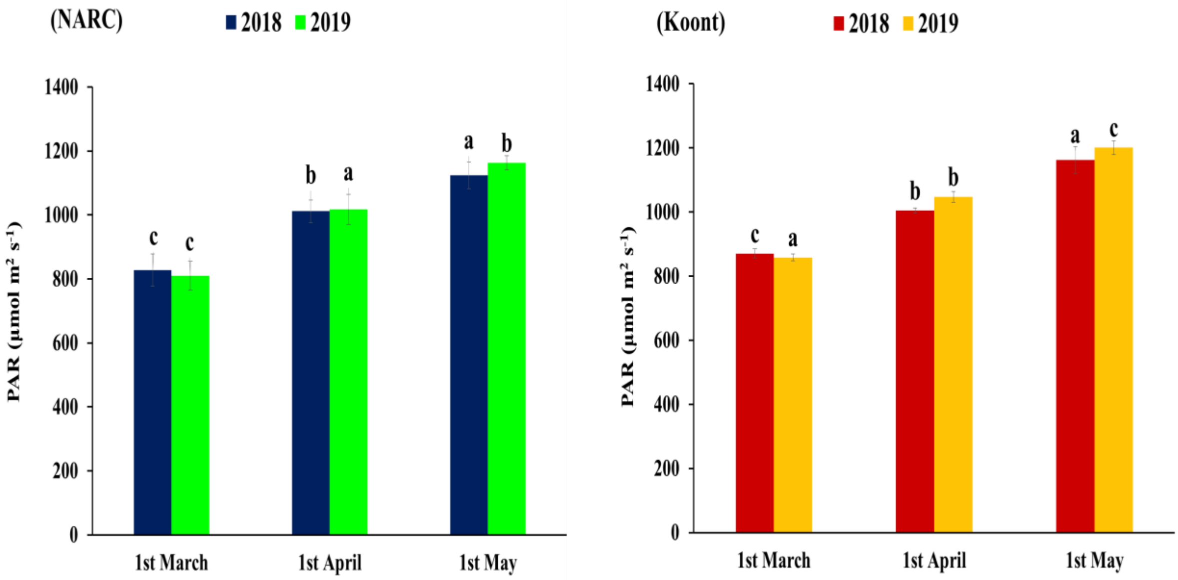

Figure 2. Effect of different sowing dates and locations on photosynthetic active radiations PAR (µmol m^2 s^{-1}) of Bambara groundnut under rainfed conditions.

3.3. Effect of different sowing dates on net photosynthetic rate pn (µmol CO_2 m^{-2} s^{-1}) of Bambara Groundnut

Data related to net photosynthetic rate pn (µmol CO_2 m^{-2} s^{-1}) presented in (Figure 3). At NARC, it was observed that pn was 21 µmol CO_2 m^{-2} s^{-1} in 1st March during both years; however, it was statistically significant to 1st April and non-significant to 1st May (Figure 4). Therefore, pn was higher 29 µmol CO_2 m^{-2} s^{-1} (2018) and 26 µmol CO_2 m^{-2} s^{-1} (2019) in 1st April, while it was 24 µmol CO_2 m^{-2} s^{-1} (2018) and 22 µmol CO_2 m^{-2} s^{-1} (2019) in 1st May. At Koont, pn was higher 31 µmol CO_2 m^{-2} s^{-1} (2018) and 29 µmol CO_2 m^{-2} s^{-1} (2019) in 1st April that is statistically significant to other sowing dates. However, non-significant change

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observed by 24 and 19 μmol CO_2 m^{-2} s^{-1} (2018) on 1st March and 1st May. Surprisingly, it was 22-23 μmol CO_2 m^{-2} s^{-1} (2019) on 1st March and 1st May. Overall, pn was high in 1st April as compared to other sowing dates.

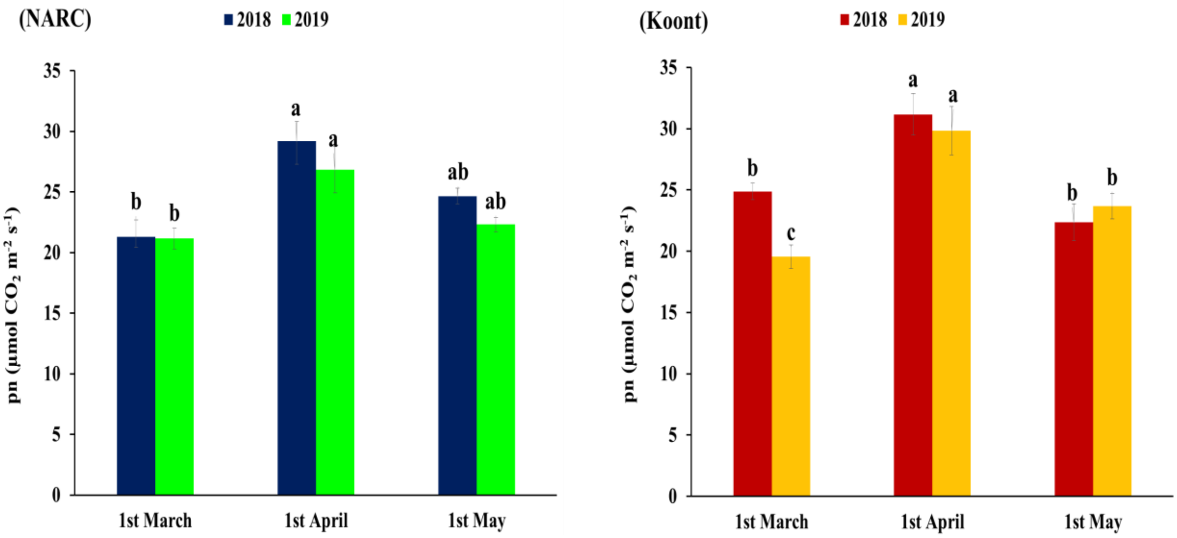

Figure 3. Effect of different sowing dates and locations on net photosynthetic rate pn (μmol CO_2 m^{-2} s^{-1}) of Bambara groundnut under rainfed conditions.

3.4. Effect of different sowing dates on net transpiration rate Tr m mol m^{-2} s^{-1} of Bambara Groundnut

At NARC, net transpiration rate (Tr) was lower in 1st April by 1.86 m mol m^{-2} s^{-1} (2018) and 1.71 m mol m^{-2} s^{-1} (2019); however, it was statistically significant to 1st March and non-significant to 1st May (Figure 4). Conversely, our results showed that Tr was 2.83-2.45 m mol m^{-2} s^{-1} (2018) and 2.23-2.73 m mol m^{-2} s^{-1} (2019) in 1st March and 1st May, but it was non-significant among each other. At Koont, Tr was significantly lower in 1st April 1.75 m mol m^{-2} s^{-1} (2018) and 1.83 m mol m^{-2} s^{-1} (2019), while it was 2.16 m mol m^{-2} s^{-1} (2018) and 2.29 m mol m^{-2} s^{-1} (2019). Notably, it was observed that Tr was significantly higher 3.07 m mol m^{-2} s^{-1} (2018) and 3.05 m mol m^{-2} s^{-1} (2019) in 1st May respectively. Generally, crop sown on 1st April potentially control transpiration rate.

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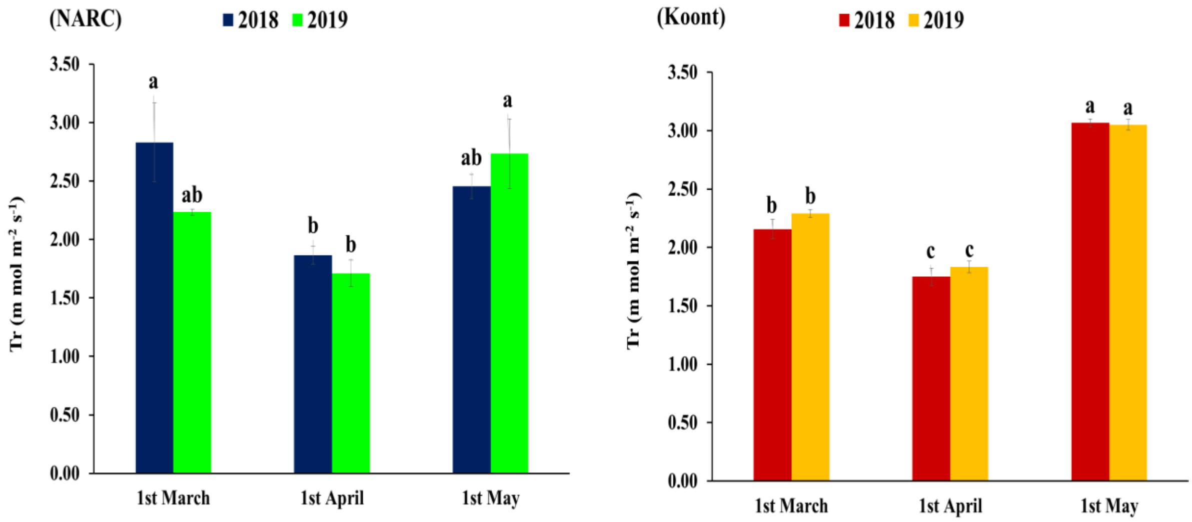

Figure 4. Effect of different sowing dates and locations on transpiration rate Tr (m mol m-2 s-1) of Bambara groundnut under rainfed conditions.

3.5. Effect of different sowing dates on relative water content RWC (%) of Bambara Groundnut

Data showed that relative water content (RWC) was changed under different sowing dates. At NARC, during 2018, data showed that RWC was significantly higher 86-85% on 1st April as shown in (Figure 5). During 2019, RWC was significantly higher by 85% on 1st April compared to other sowing dates. At Koont, during both years, RWC was higher 82% in 1st April.

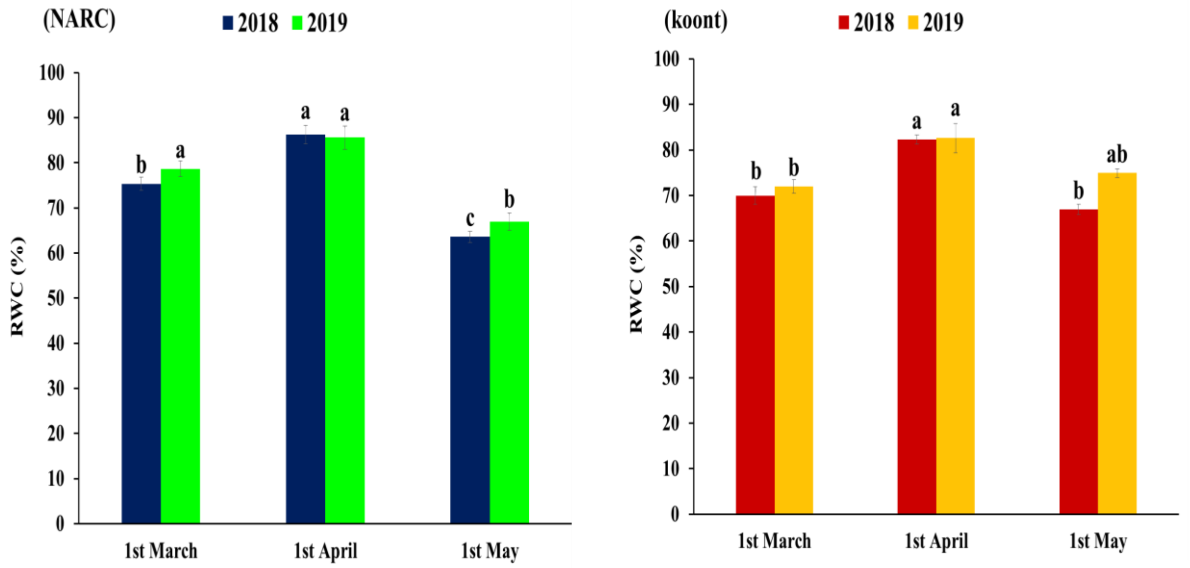

Figure 5. Effect of different sowing dates and locations on relative water content RWC (%) of Bambara groundnut under rainfed conditions.

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3.6. Effect of different sowing dates on days to maturity of Bambara Groundnut

Days to maturity was significantly varied in different sowing dates as shown in Figure 6. At NARC, during 2018, days to maturity was significantly higher 145 on 1st April over other sowing dates respectively. During 2019, days to maturity was significantly higher 141.3 on 1st April. Notably, at Koont, during 2018, days to maturity was significantly higher 146 on 1st April as compared to other sowing dates. Similarly, during 2019, it was observed that crop sown on 1st April significantly showed highest 143 days to maturity rather than 130.6 on 1st May and 121.6 on 1st March respectively.

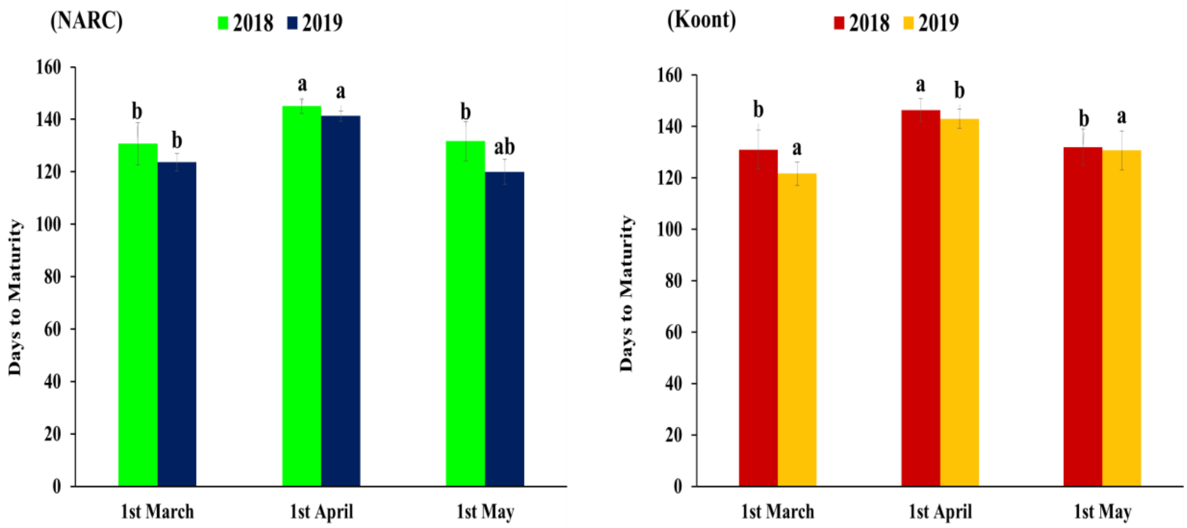

Figure 6. Effect of different sowing dates and locations on days to maturity of Bambara groundnut under rainfed conditions.

3.7. Effect of different sowing dates on morphological traits of Bambara Groundnut

During both years and locations, various plant morphological traits associated with physiological traits on different sowing dates were represented in Table 2. At NARC, plant height (cm) was significantly highest at 28cm (2018) and 29 cm (2019) in 1st April, followed by 17–19 cm and 16 cm in 1st March and 1st May. However, during 2018, a significant variation was observed between 1st March and 1st May, while it was non-significant during 2019. For leaf length (cm), it was observed that 1st April showed a significantly higher 8.25 cm leaf length (2018) as compared to 2.39 cm in 1st March and a non-significant 4.49 cm in 1st May; however, it was non-significant between 1st March and 1st May. It was significantly higher at 7.15 cm in 1st April (2019), followed by 5.52 cm in 1st May and 3.82 cm in 1st March. Similarly, leaf width (cm) was significantly higher at 3.93 cm (2018) in 1st April compared to 3.14 cm in 1st March and 3.55 cm in 1st May. It was noticed that 1st April

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showed a maximum 4.18 cm leaf width; however, it was non-significant to 3.27 cm in 1st March and 3.39 cm in 1st May, respectively. At Koont, plant height (cm) was maximum 22.5 cm (2018) and 24.6 cm (2019) in 1st April, while it was 19.5–15 cm (2018) and 21.8–17.2 cm (2019) in 1st March and 1st May; however, it was significant in (2018) and non-significant in (2019). Notably, it was observed that leaf length (cm) was a maximum 7.92 cm (2018) and 7.48 cm (2019) in 1st April, which were significant, while it was 2.39–4.49 cm (2018) and 3.82–5.52 cm (2019) in 1st March and 1st May. Leaf length (cm) was found to be non-significant in May 1st (2018), but significant in 2019. Similarly, it was noticed that leaf width (cm) was at its maximum of 4.28 cm (2018) and 4.18 cm (2019) in April 1st, while it was 3.14–3.69 cm (2018) and 3.55–3.08 cm (2019), in 1st March and 1st May respectively. Additionally, it was indicated that 1st April significantly varied to 1st March (2018) and 1st May (2019), while 1st March was non-significant to 1st May during both years. As a whole, 1st April gave potential results in plant morphological traits, followed by 1st March and 1st May, respectively.

3.8. Effect of different sowing dates on yield components of Bambara Groundnut

Various plant yield related traits were presented in Table 3. For NARC, mean data showed that the number of branches was maximum 73 in 1st April during both years, while it was 67.33–70.67 cm (2018) and 68.67–69.33 cm (2019) in 1st March and 1st May. However, 1st April showed significant variation from 1st March and was non-significant from 1st May (2018), and it was significantly varied from other sowing dates (2019). Remarkably, it was noticed that the number of pods was significantly higher (31.1 cm in 1st April) than 23.2 cm in 1st March and 25.6 cm in 1st May (2018); however, non-significant variation was observed between 1st March and 1st May, respectively. During 2019, 1st April showed significant variation from 29.2 cm to 19.7 cm in 1st May; however, it showed non-significant variation to 1st May, as shown in Table 3. Interestingly, biomass (kg ha^{-1}) was 10020.75 kg ha^{-1} (2018) and 10013.30 kg ha^{-1} (2019) in 1st April, while it was 9764.77-9960.93 kg/ha (2018) and 9719.89-9887.40 kg ha^{-1} (2019) in 1st March and 1st May, respectively. However, 1st April showed significant variation from 1st March and was non-significant from 1st May (2018). In addition, all treatments showed non-significant variations (2019). Similarly, the higher seed yield (kg ha^{-1}) was 2040.77 kg ha^{-1} (2018) and 1972.88 kg ha^{-1} (2019), while it was 1992.97–1760.43 kg ha^{-1} (2018) and 1931.16–1918.22 kg ha^{-1} (2019) in 1st March and 1st May. However, all treatments are significantly varied (2018), while it showed significant variation to 1st May (2019) and non-significant variation to 1st March (2018). At Koont, the number of branches per plant was 76 (2018) and 77.33 (2019) in 1st April, while it was 71.33–70.17 (2018) and 70.33–77 (2019), in 1st March and 1st May, respectively. However, all treatments showed a non-significant difference (2018), while 1st April showed variation from other

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sowing dates. In addition, the number of pods was 28.66 (2018) and 28.37 (2019) in 1st April, while it was 20.73-22.66 (2018) and 24.59-26.48 (2019) in 1st March and 1st May. However, 1st April showed significant variation from 1st March and was non-significant from 1st May (2018). All treatments showed significant variation during 2019.

Plant biomass kg ha^{-1} was also significantly higher at 10056.20 kg ha^{-1} than 9701.7 kg ha^{-1} in 1st March and 6734.04 kg ha^{-1} in 1st May (2018); however, no significant difference was observed between 1st March and 1st May. During 2019, 1st April was significantly higher at 10008.6 kg ha^{-1} as compared to 9643.3 kg ha^{-1} in 1st March and 9759.2 kg ha^{-1} in 1st May. Notably, seed yield kg ha^{-1} was significantly higher at 1974.3 kg ha^{-1} in 1st April rather than 1920.8 kg ha^{-1} in 1st March and was non-significant at 1947.2 kg ha^{-1} on 1st May. During 2019, seed yield (kg ha^{-1}) was maximum at 1979.4 kg ha^{-1}, followed by 1934.02 kg ha^{-1} in 1st March and 1924.1 kg ha^{-1} in 1st May; however, all treatments showed a non-significant difference. Overall, the crop showed a promising response in increasing the seed yield and other yield components on 1st April as compared to other sowing dates.

3.9. Effect of different sowing dates on seed oil content (%) of Bambara Groundnut

Data showed that seed oil content (%) was changed under different sowing dates. At NARC, during 2018 and 2019, seed oil content (%) was significantly higher 6.4-6.5% in 1st April as shown in (Figure 7). In addition, the lower value 4.98-5.02% in 1st May. At Koont, seed oil content (%) was higher 7.7-7.9% in 1st April during both years. Whereas, the lower value 5.98-6.10% in 1st May.

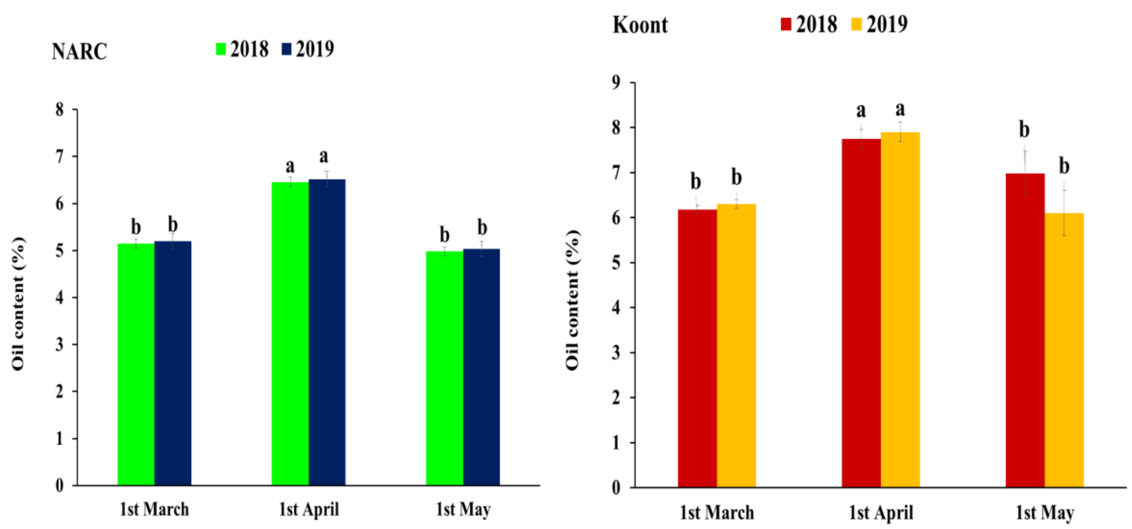

Figure 7. Effect of different sowing dates and locations on seed oil content (%) of Bambara groundnut under rainfed conditions.

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3.10. Effect of different sowing dates on seed protein content (%) of Bambara Groundnut

Data showed that seed protein content (%) was changed under different sowing dates. At NARC, during 2018 and 2019, seed protein content (%) was higher 30-32% in 1st April. It was noticed that seed protein (%) was lower 23.44-22.26% in 1st May respectively. At Koont, seed protein content (%) was higher 33-34% in 1st April during both years. Surprisingly, the lower seed protein (%) 25.17-26.71% was observed in 1st May as shown in (Figure 8).

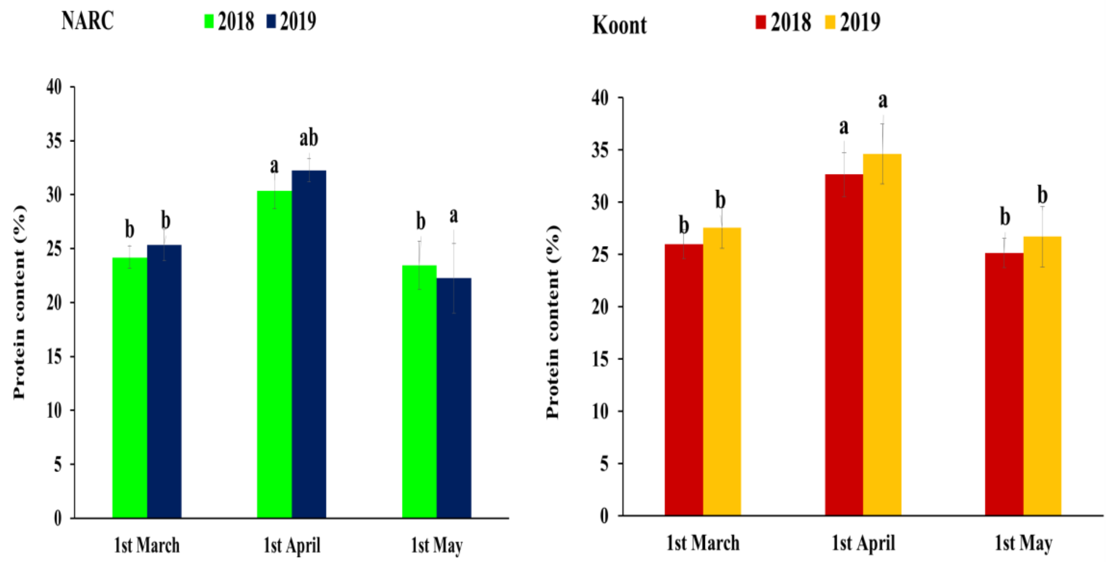

Figure 8. Effect of different sowing dates and locations on seed protein content (%) of Bambara groundnut under rainfed conditions.

Table 3. Effect of different sowing dates and locations on various morphological and yield traits of Bambara groundnut during 2018-19 and 2019-20.

		Sowing dates		
Parameter	**Year/ Location**	**1st March**	**1st April**	**1st May**
Plant Height (cm)	**2018**			
	NARC	17.13 ± 0.92b	28.23 ± 1.54a	15.50 ± 1.12b
	Koont	19.50 ± 1.70b	22.57 ± 1.57a	15 ± 1.16c
	2019			
	NARC	19.13 ± 0.77b	29 ± 1.38a	16.03 ± 1.42c
	Koont	21.83 ± 2a	24.60 ± 3.29a	17.27 ± 1.32a
Leaf Length	**2018**			
	NARC	2.39 ± 1.19b	8.25 ± 0.94a	4.49 ± 1.28ab

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(cm)	Koont	3.43 ± 0.70b	7.92 ± 0.67a	5.16 ± 0.75b
	2019			
	NARC	3.82 ± 0.54c	7.15 ± 0.48a	5.52 ± 0.29b
	Koont	3.82 ± 0.54c	7.48 ± 0.72a	5.52 ± 0.29b
Length Width (cm)	2018			
	NARC	3.14 ± 0.14c	3.93 ± 0.27a	3.55 ± 0.19b
	Koont	3.16 ± 0.36b	4.28 ± 0.35a	3.69 ± 0.29ab
	2019			
	NARC	3.27 ± 0.49b	4.18 ± 0.35a	3.39 ± 0.29ab
	Koont	3.55 ± 0.21ab	4.18 ± 0.26a	3.08 ± 0.35b
Number of Branches	2018			
	NARC	67.33 ± 1.78b	72.67 ± 1.91a	70.67 ± 1.19a
	Koont	71.33 ± 2.13a	76 ± 2.62a	70.17 ± 1.42a
	2019			
	NARC	68.67 ± 0.54b	73 ± 0.94a	69.33 ± 0.98b
	Koont	70.33 ± 1.66b	77.33 ± 2.68a	73 ± 2.45b
Number of Pods	2018			
	NARC	23.25 ± 0.53b	31.11 ± 1.07a	25.65 ± 1.34b
	Koont	20.73 ± 0.64a	28.66 ± 1.26b	22.66 ± 1.97ab
	2019			
	NARC	25.46 ± 2.53ab	29.29 ± 1.63a	19.73 ± 1.77b
	Koont	24.59 ± 2.42c	28.37 ± 2.79a	26.48 ± 2.47b
Seed Yield (kg ha^{-1})	2018			
	NARC	1992.9 ± 3.47b	2040.7 ± 16.22a	1760.4 ± 14.14c
	Koont	1920.8 ± 70.66b	1974.39 ± 74.35a	1947.2 ± 71.90ab
	2019			
	NARC	1931.16 ± 68.36ab	1972.88 ± 75.45a	1918.22 ± 78.22b
	Koont	1934 ± 65.95a	1979.48 ± 74.82a	1924.18 ± 74.90a
Biological Yield (kg ha^{-1})	2018			
	NARC	9764.7 ± 38.99a	10020.7 ± 1.10b	9960.9 ± 74.47ab
	Koont	9701.7 ± 12.76b	10056.2 ± 26.93a	9734 ± 26.93b
	2019			

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NARC	9719.8 ± 89.12b	10013.3 ± 6.31ab	9887.4 ± 78.03a
Koont	9643.5 ± 15.83a	10008.6 ± 23.28b	9759.2 ± 22.99c

Means are average of three biological replications and alphabet lettering shows significant or non-significant difference within treatments using LSD test (p≤0.05).

3.11. Correlation analysis

The pearson correlation analysis showed the positive and negative correlation among all parameters of Bambara groundnut as shown in Fig. 9. The SY showed the strong positive correlation with RWC (0.7) and gs (0.6), while it showed strong negative correlation with Tr and PAR (0.3) respectively.

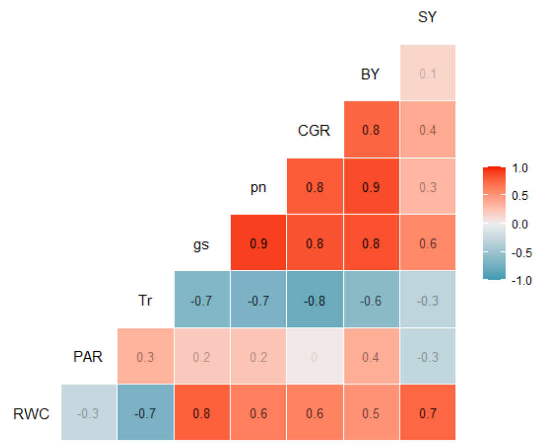

Figure 9. The pearson correlation among all parameters including relative water content (RWC), photosynthetic active radiation (RAR), tr (transpiration rate), gs (stomatal conductance), pn (net photosynthetic rate), crop growth rate (CGR), biological yield (BY) and seed yield (BY). The values from (0 to +) showed positive correlation and (0 to -) showed negative correlation.

3.12. Principle components analysis (PCA)

The principle component analysis (PCA) showed the selection of effective sowing date and environment. In figure 10a, the sowing date 1st April at both locations NARC and Koont showed the excellent results as it comes on axes. In figure 10b, the Bambara groundnut showed perfect growth performance at location Koont over NARC.

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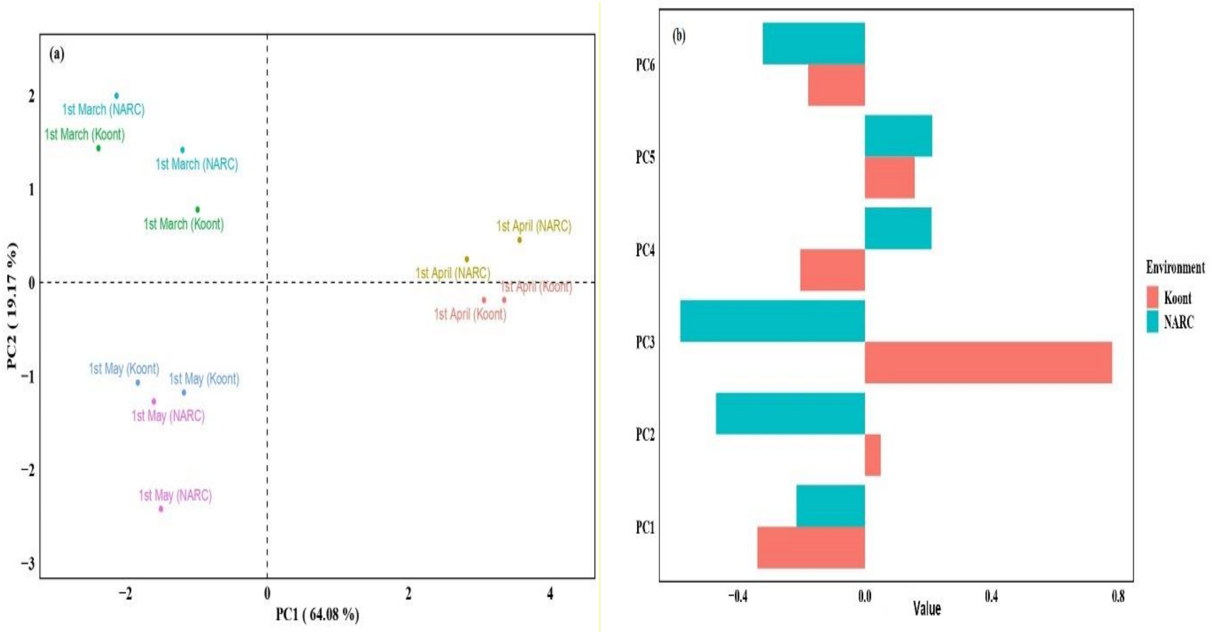

Figure 10. The principle component analysis (PCA) to (a) evaluate best sowing date (b) to evaluate the best sowing environment.

4. Discussion

In this study, we introduced the Bambara groundnut and checked its adaptability in the Pothwar region of Pakistan under different sowing dates and locations during 2018 and 2019. However, we evaluated the best performance of Bambara groundnut in 1st April, suggesting its promising growth and production under this sowing date as shown in Figure 10a. In addition, the location Koont showed much favorability over NARC as proved with PCA analysis Figure 10b. The effect of sowing dates on stomatal conductance (gs), an essential parameter that indicates gaseous exchange in plants (Wang et al., 2022). We observed that gs increased in 1st April due to environmental changes, plant developmental stages, and soil moisture availability, enabling efficient transpiration through stomata opening (Qi et al., 2023). Previous study by (Huang et al., (2021) reported the influence of varying environmental factors on gs of plants. The variation in gs could lead to a significant influence on the seed yield of Bambara groundnut, as shown in Figure 9. Photosynthetic active radiation (PAR) indicates the exposure of light on crop leaves, varying by varying sowing dates (Noriega Gardea et al., 2021). According to our results, low PAR in 1st March caused inefficient CO_2 assimilation, while high PAR in 1st May caused high temperatures and stress conditions for Bambara groundnut as shown in Figure 2 and 9. The similar observations were noted by Gautam et al. (2019); Ziaei Ghahnavieh et al. (2023), stated that PAR fluctuations significantly affect the growth and seed yield of plants. Interestingly, optimum PAR was observed on crop sown in 1st April which could lead to increased net photosynthetic rate (pn).

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Net photosynthetic rate (pn) is a vital parameter that indicates the ability of plant to convert light energy into chemical energy (Yue et al., 2023). Our observations revealed that the pn was remarkably highest on 1st April over other sowing dates, which could be direct association of sowing dates with photosynthetic efficiency, as shown in Figure 3 and 9. The increased pn of plants sown in 1st April may have experienced optimum temperature and appropriate light intensity. According to Kettler et al. (2022); Zhen et al. (2020), direct relationship between pn and PAR indicated that the influence of light (temperature) on photosynthetic rate has a significant impact on plant growth and yield production. In addition, the variation in transpiration rate could have influence on photosynthetic activities of plants (Mansour et al., 2021).

Net transpiration rate (tr) is an essential factor to estimate the water loss from stomata of leaves through transpiration (Fujiuchi et al., 2022). The remarkable reduction in transpiration rate observed in 1st April, clearly indicates its complex relationship between the sowing dates and water management features of plants as shown in Figure. 4. (Blankenagel et al., 2018) stated that decrease in transpiration rate could be due to the adaptation of plants to optimization of water utilization. According to Sun et al. (2023), favorable environmental factors contribute to reduction in water loss through transpiration, allowing stomata to partially close and promoting optimal photosynthetic rates.

Relative water content (RWC) is an important parameter that indicates the cell water status of plant tissue (Zegaoui et al., 2017). However, crop sown in 1st April showed higher RWC, which could be due to adequate water uptake, optimized utilization and reduced water loss associated with the transpiration rate (Coleman et al., 2023; Qiao et al., 2022). Furthermore, younger leaves exhibited better water use efficiency and governing mechanism, which resulted in a high relative water content (Zhao et al., 2023). Remarkably, the decreased RWC in 1st March and 1st May are due to varying environmental conditions associated with soil conditions which could lead to reduction in seed yield of crop.

Sowing dates significantly influenced Bambara groundnut days to maturity highlighting the intricate relationship between sowing dates and crop growth cycle duration (Borowska & Prusiński, 2021). However, the extended maturity days on crop sown 1st April may be due to promising conditions like optimum temperatures and light availability as shown in Figure. 6. According to De Rességuier et al. (2020); Van Dyck et al. (2023), these conditions may cause plants to conserve more resources and utilize them efficiently in growth and flower formation, leading to an extended crop growth cycle. Remarkably, days to maturity were decreased by crop sown on other sowing dates which might be due to varied environmental conditions and potentially hastened reproductive stage, resulting in an early maturity. The seed oil and protein contents were also altered in different sowing dates at both locations as shown in Figure 7 and 8.

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This comprehensive study examined the different sowing dates on Bambara groundnut by focusing on various morphological and yield traits. Collectively, all these traits were increased on crop sown 1st April as compared to 1st March and 1st May, highlights the multifaceted impacts of sowing dates on growth, development and overall productivity of Bambara groundnut. This highlights the crow owing time linked with increased vegetative, resulting in an efficient seed yield per hectare on the crop sown 1st April as compared to others. Previous studies by (Alshareef et al. (2018); Olanrewaju et al. (2021) reported the performance of Bambara groundnut yield components on different sowing dates. This research demonstrates that the selection of the 1st April sowing time for Bambara groundnut, taking into account several plant morph-physiological and yield features, has promise for enhancing total yield output and promoting sustainability.

5. Conclusion

In conclusion, this study explored the complicated interaction between various sowing dates and morphological, physiological, and yield-related aspects of Bambara groundnut. The results cumulatively emphasized the supreme importance of selecting the best sowing date as a vital consideration for crop performance and production. Among sowing dates, the 1st of April demonstrated the best performance, underscoring the prominence of the crop in an optimum and favorable environmental condition. The environmental factors, including optimum temperature, light, and soil conditions interaction, played a key role in enhancing the growth and development of Bambara groundnut and clearly indicated how this sowing date can improve resource utilization and increase crop yield. This current study gives practical guidelines to the farmer community and agricultural scientists on the impact of sowing dates on Bambara groundnut, allowing knowledgeable resource use, risk alleviation, and sustainable crop production, and positioning the foundation for upcoming research.

6. Future perspective

This study presents novel methodologies for enhancing future research and applications within agricultural systems. Nevertheless, it is crucial to comprehend the complicated interaction between environmental factors and the timing of sowing in light of evolving climatic circumstances. Additional research might be conducted to explore the genetic and molecular factors that influence the response of plants to particular sowing timings, therefore enabling the development of crop varieties that exhibit optimum performance. Furthermore, forthcoming observations provide probability for enhancing agricultural methodologies, enabling robust and sustainable crop cultivation by strategic use of dates, and integrating scientific, technological, and data-driven perspectives.

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