Original Research Article

Effects of Sowing Dates, and Planting Densities on Yield Attributes of Groundnut (*Arachis hypogaea* L.) in Hot Arid Region of India, Insights into Enhancing Groundnut Yields in Changing Climate Scenario

Comment [U1]: May change with new title Optimizing Groundnut (*Arachis hypogaea* L.) Yields: An impact of Sowing Dates and Planting Densities in India's Hot Arid Regions Under a Changing Climate

ABSTRACT

Groundnut (*Arachis hypogaea* L.) holds immense significance as an oilseed crop on a global scale. The growth and development of plants, along with crop productivity, are substantially impacted by the adverse effects of global climate change. In view of this, a research initiative was undertaken to investigate the effects of distinct sowing dates and planting densities on the yield and economic aspects of groundnut in the hot arid region of Rajasthan, India. The experiment, conducted over a span of three years during the kharif seasons of 2017, 2018, and 2019 at Swami Keshwanand Rajasthan Agricultural University, Bikaner, Rajasthan, India. The experimental design utilized a split-plot layout with four replications, comprising nine treatments. The main plot treatments involved three different sowing dates (15th May, 30th May, and 15th June), while the sub-plot treatments encompassed three planting densities (1.67 lakh, 2.50 lakh, and 3.33 lakh plants per hectare). Notably, the diverse sowing dates and planting densities exhibited notable effects on groundnut's yield components, overall yield, and economic viability. Comparative analysis revealed that sowing on May 30th, while statistically comparable to June 15th sowing, yielded the highest number of branches, pegs, pods per plant, kernel and pod yield, net return, and benefit-cost ratio. This performance was notably superior to that of the May 15th sowing. Interestingly, the highest haulm yield per hectare was achieved with the May 15th sowing, yet the harvest index improved progressively as sowing was delayed from May 15th to June 15th. However, the various sowing dates had no discernible effect on kernels per pod, seed index, and shelling percentage. Furthermore, employing a planting density of 1.67 lakh plants per hectare ~~resulted~~was resulted in the highest counts of branches, pegs, pods, kernels per pod, seed index, and shelling percentage. This performance significantly outshone the outcomes associated with planting densities of 2.50 and 3.33 lakh plants per hectare. ~~Notably, T~~the elevation in planting density up to 2.50 lakh plants per hectare led to enhanced kernel and pod yields, harvest index, and net return. A planting density of 3.33 lakh plants per hectare, on the other hand, maximized haulm yield. In an intriguing interaction between sowing dates and plant populations, the most favorable pod yield, kernel yield, and net return were recorded with a planting density of 2.50 lakh plants per hectare for the May 30th sowing. These findings underscore the significant effect of sowing date and planting density on yield attributes and ultimately on groundnut yield in the challenging hot arid region. Therefore, the timing of sowing and the density of planting play pivotal roles in enhancing groundnut productivity within this region, particularly in light of the changing climate conditions.

Keywords, Groundnut, economics, planting density, time of sowing, yield

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1. INTRODUCTION

Groundnut (*Arachis hypogaea* L.) stands as a significant legume crop on a global scale [1, 2]. Groundnut cultivated in tropical, subtropical, and temperate climates, holds significance as an essential oilseed, confectionery, and livestock crop [3, 4]. Global groundnut production reaches approximately 50.7 million tonnes annually, cultivated across 26.4 million hectares of land [5]. Groundnut holds a crucial position as an oilseed crop in India, where it takes the lead in terms of cultivation area and secures the second position in production, right after soybean. China takes the lead in groundnut production with 17.57 million tonnes, closely trailed by India with 6.73 million tonnes (FAO, 2021). The seeds of groundnut are rich in essential nutrients, encompassing approximately 44–56% oil and 22–30% protein content [6, 7]. Additionally, groundnut seeds serve as a valuable reservoir of calcium, phosphorus, iron, and vitamins [8]. Additionally, groundnut serves as a significant source of animal feed, both in the form of haulms and groundnut cake. Moreover, its suitability for crop rotation is notable, given its ability to facilitate atmospheric nitrogen fixation, which proves advantageous for subsequent crops [9]. The growth and development of groundnut are intricately influenced by a multitude of uncontrollable environmental factors. Optimal diurnal air temperatures for groundnut's photosynthesis and vegetative growth fall within the range of 30 to 35°C, as documented by Prasad et al. [10] and Craufurd *et al.* [11]. In contrast, the ideal diurnal temperature for reproductive growth and eventual yield is somewhat cooler, approximately 25 to 28°C, according to Ketring [12] and Prasad et al. [10]. Elevated daytime temperatures surpassing 35°C during the reproductive phases have been shown to diminish dry matter production, the formation of flowers into pegs, pod count per plant, individual seed size, harvest index, and pod yield, as demonstrated by Craufurd *et al.* [11], Ketring [12], and Prasad et al. [10, 13]. The duration of daylight significantly influences the growth dynamics. Longer days (exceeding 13 hours) enhance vegetative growth and crop growth rate, while reducing the allocation of photosynthate to pods. Conversely, shorter days (less than 12 hours) foster an increase in the number of flowers, pegs, and pods in groundnut, as highlighted by Bagnall and King [14, 15] and Nigam et al. [16]. In addition, incident solar radiation and the duration of sunshine play pivotal roles in shaping the growth and development of groundnut [14-16].

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Cultivar selection, sowing timing, and the duration of a cultivar's lifecycle are all crucial factors in managing a crop, impacting the growth, yield, and seed quality of groundnut. Among these, the timing of sowing holds particular significance as it can be manipulated to mitigate the negative impact of environmental stress. By strategically adjusting sowing dates, it is possible to avoid subjecting plants to ~~unfavorable~~unfavourable environmental conditions during critical growth stages. Sowing date and planting density research for groundnut has been conducted in various groundnut-growing nations worldwide [4, 17-22] Achieving a substantial groundnut yield and ensuring profitable economic outcomes hinge significantly on optimal plant density, which defines the spacing between individual plants. Several authors have underscored the significance of higher plant densities for achieving the highest or most favorable groundnut yields [23-27]. In the Indian context, specific recommendations have been put forth, such as an optimal population of 330,000 plants per hectare (with a spacing of 30 cm × 10 cm) for Spanish/Valencia cultivars, and 148,000 plants per hectare (with a spacing of 45 cm × 15 cm) for Virginia cultivars [23]. Plant density plays a significant role in governing growth, pod production rate, and the eventual pod and kernel yield in groundnut cultivation [28]. Utilizing low plant population density often leads to reduced yields, whereas higher population densities coupled with better management practices can potentially yield a remarkable increase in pod production, sometimes reaching as high as 150-250%. The objective of plant population studies in crop plants is to ascertain the optimal plant density that yields maximum productivity [29]. Manipulating the planting date emerges as a crucial element of production that can be strategically adjusted to mitigate the detrimental impacts of environmental stress. Aligning the crop's phenology with favorable conditions by meticulously selecting appropriate sowing dates to bypass periods of stress becomes pivotal for maximizing yield. The fine-tuning of sowing dates holds great significance in optimizing the climatic environment with respect to the growth and yield of the groundnut crop, as emphasized by Caliskan et al. [4].

Many of these studies aimed to counteract drought or high-temperature stress that could occur during pivotal groundnut growth phases by adapting the sowing schedule. However, investigations specifically focusing on the effects of sowing dates and related environmental variables on groundnut growth and yield in hot arid regions are relatively scarce. The productivity of the crop is inherently linked to the interplay during its growth phases, a relationship intricately tied to the timing of sowing. Identifying the optimum sowing time for groundnut enables the adjustment of growth phase durations to align with favorable weather conditions [30]. Further, the choice of sowing date is contingent on the local conditions, with significant influence stemming from factors such as soil temperature, available

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soil moisture, and the prevailing growing season. In India, groundnuts are typically sown during the rainy season, commencing with the onset of rains between May and June. In the Hyper Arid Zone of Rajasthan, there is a growing emphasis on cultivating groundnut during the kharif season. However, due to the absence of well-defined sowing schedules and standardized plant populations, farmers tend to resort to heavy seed rates, even exceeding 240 kg per hectare. Despite its costliness, this practice has become prevalent. The current study aims to address this gap by precisely assessing the effect of planting times and densities on both the agronomic and economic aspects of groundnut cultivation within the challenging hot arid context. This ~~three-year experiment was conducted at Swami Keshwanand Rajasthan Agricultural University, Bikaner, Rajasthan. It evaluated the effects of planting time and density on groundnut yield and economic returns in the hot arid climate. The experiment incorporated three distinct planting dates, May 15th, May 30th, and June 15th, alongside three planting densities (1.67, 2.50, and 3.33 lakh plants per hectare) in a split-plot design with four replications. These results indicated significant variations in yield components, overall yield, and economic feasibility due to the different sowing dates and planting densities. This underscores the pivotal roles of both sowing date and planting density in shaping groundnut yield in the challenging hot arid region. Collectively, these findings demonstrated that the timing of sowing and the choice of planting density emerge as crucial factors for enhancing groundnut productivity in this specific region, particularly in light of the evolving climate conditions.~~

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2. MATERIALS AND METHODS

2.1 Experimental Site

Field experiments were conducted during the kharif seasons of 2017, 2018, and 2019 at the instructional farm of Krishi Vigyan Kendra in Bikaner, Rajasthan. The location is situated at 28° 01'N latitude and 73° 22'E longitude, at an elevation of 234.70 meters above mean sea level. The site experiences a hot arid climate with an annual rainfall of 263.5 mm, falling under the category of hyper arid conditions. The soil at the experimental site is classified as loamy sand, with nutrient content of 258.7 kg/ha N, 17.4 kg/ha available P, 223.4 kg/ha K, and 0.79% organic carbon. The pH of the soil was measured at 8.3 using a 1,2.5 soil-to-water ratio. Soil properties in the 0-30 cm depth included a field capacity of 8.3%, a permanent wilting point of 1.83%, and a bulk density of 1.67 Mgm-3. The meteorological parameters observed throughout the growth and development of groundnut are presented in Table 1 and depicted in Figure 1.

Table 1: The average monthly meteorological data observed throughout the crop periods of 2017, 2018, and 2019.

Months	Temperature (°C)						R.H. (%)						Total rainfall (mm)		
	Max.			Min.			RH1			RH2					
	2017	2018	2019	2017	2018	2019	2017	2018	2019	2017	2018	2019	2017	2018	2019
May	42.9	43.7	41.4	26.8	27.0	25.4	54.6	36.0	72.2	27.3	18.2	53.5	19.2	5.6	9.0
June	39.8	41.3	43.4	27.5	28.7	29.4	69.7	62.3	85.9	38.5	35.4	66.8	123.0	54.3	12.8
July	38.4	37.8	39.8	27.5	28.1	28.7	78.7	84.1	77.4	47.4	51.3	55.2	29.3	189.8	40.6
August	37.4	36.2	36.3	26.7	26.6	26.7	76.1	82.5	84.2	47.5	50.4	63.9	90.6	54.8	128.2
September	37.8	36.5	38.0	24.0	24.0	26.0	71.8	69.6	87.4	36.5	41.2	60.9	6.0	0.0	16.2
October	38.7	36.6	34.6	18.4	18.6	18.6	49.2	55.0	71.6	20.4	21.7	39.5	0.0	0.0	28.8
November	30.4	30.8	27.1	11.2	11.4	12.8	69.7	69.6	84.2	27.2	27.4	48.6	1.4	0.8	27.2

Source: Agricultural Research Station, Bikaner

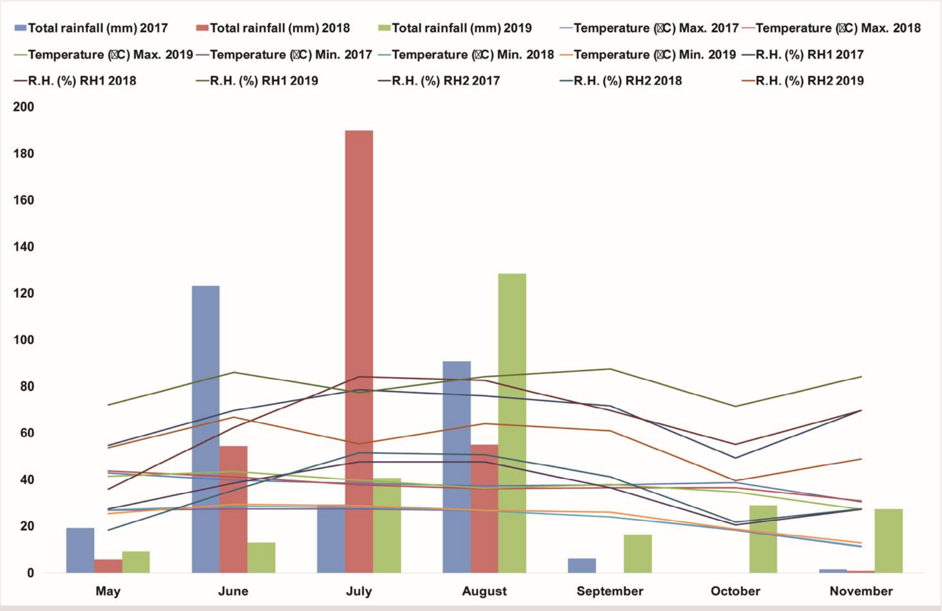

Figure 1: Monthly meteorological averages throughout the crop seasons of 2017, 2018, and 2019.

The monthly average maximum temperatures (T max) showed variations within the ranges of 42.9°C to 30.4°C in 2017, 43.7°C to 30.8°C in 2018, and 43.4°C to 27.1°C in 2019. Concurrently, the minimum temperatures (T min) ranged between 11.2°C and 27.5°C in 2017, 11.4°C and 28.7°C in 2018, and 12.8°C and 29.4°C in 2019. Notably, the highest maximum temperature was recorded in May, while the lowest minimum temperature was observed in November, both within the growing periods. Relative humidity data revealed morning relative humidity (RH-I) fluctuations from 49% to 78.7%, 36.0% to 84.1%, and 71.6% to 87.4% for the years 2017, 2018, and 2019 respectively during the growing periods. As for afternoon relative humidity (RH-II), the range spanned from 27.2% to 47.5% in 2017, 18.2% to 51.3% in 2018, and 39.5% to 66.8% in 2019. The maximum rainfall was received during the months of June to August, encompassing the growing period.

2.2 Treatment

The experimental design utilized a split-plot layout with four replications, comprising nine treatments. The main plot treatments involved three different sowing dates (15th May, 30th May, and 15th June), while the sub-plot treatments encompassed three planting densities (1.67 lakh, 2.50 lakh, and 3.33 lakh plants per hectare). Groundnut variety HNG-69 was sown according to the specified sowing dates at different planting densities, with corresponding seed rates of 80 kg, 120 kg, and 160 kg per hectare for the respective density treatments. The recommended ~~amounts~~ dose of nitrogen (20 kg N/ha) and phosphorus (40 kg P2O5/ha) fertilizers were applied during planting. Urea and single super phosphate were used as the sources for supplying nitrogen and phosphorus nutrients, respectively. Alongside the variations in sowing dates and planting densities, the cultivation followed the prescribed package of recommended practices.

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2.3 Data Collection and Analysis

The net plots were harvested by uprooting the entire plant, including the pods, using a hoe. Any remaining pods in the soil were also collected. Subsequently, the pods were separated from the haulms and allowed to dry for about 7-8 days under direct sunlight. During the harvesting period, 20 plants were randomly selected from each plot to measure the number and weight of pods per plant. The seed yield (in kilograms per hectare) was calculated from the plants in four ridges within each plot, determining the overall yield per hectare. After harvesting, data regarding 100-kernel weight and shelling percentage were obtained, following the methodology outlined by [8]. The collected data were subjected to statistical analysis using a Split Plot Design. An analysis of variance (ANOVA) was

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performed to assess the significance of treatment effects at a 0.05% level of probability (α = 0.05). To compare means, the Least Significant Difference (LSD) test was applied at the same 0.05% significance level.

3. RESULTS AND DISCUSSION

3.1 Effect of sowing date on yield and its components across each year

Groundnut is globally significant as an oilseed crop, and its growth, development, and crop productivity face significant challenges due to the adverse impacts of global climate change. This study focuses on assessing the influence of varying sowing dates and planting densities on groundnut cultivation in the hot arid region of Rajasthan, India. Remarkably, our investigation revealed substantial effects of different sowing dates and planting densities on groundnut's yield components, overall harvest, and economic feasibility. In this study, we conducted experiments with three distinct planting dates, May 15th, May 30th, and June 15th revealed that the number of branches per plant, pegs per plant, and pods per plant were significantly influenced by different sowing dates (Table 2).

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Table 2: The effect of various sowing dates and planting densities on the yield components of groundnut, considering the pooled data from 2017 to 2019.

Treatments	Branches per plant	Pegs per plant	Pods per plant	kernels per pod	100 kernel weight (g)	Shelling %
Date of sowing						
Sowing at 15 May	9.75b	85.02b	25.98b	1.45a	45.49a	72.22a
Sowing at 30 May	12.01a	89.28a	28.68a	1.44a	45.16a	71.02a
Sowing at 15 June	11.90a	90.19a	28.71a	1.41a	44.99a	70.49a
SEm±	0.25	1.04	0.60	0.03	0.19	0.70
CD at 5%	0.75	3.09	1.79	NS	NS	NS
Planting density						
1.67 lac ha^{-1}	12.88a	94.21a	34.20a	1.54a	45.81a	76.14a
2.50 lac ha^{-1}	11.53b	91.88b	27.24b	1.39b	45.18b	69.40b
3.33 lac ha^{-1}	9.25c	78.39c	21.93c	1.37b	44.65c	68.19b
SEm±	0.22	0.91	0.56	0.02	0.17	0.77
CD at 5%	0.63	2.57	1.58	0.07	0.47	2.19

Sowing on May 30th showed statistically similar results to sowing on June 15th, producing the highest number of branches per plant, pegs per plant, and pods per plant-1, which was significantly greater than the results obtained from sowing on May 15th. The number of branches per plant, pegs per plant, and pods per plant increased with delayed sowing up to May 30th and then decreased with sowing on June 15th. These findings align with those reported by Rasekh et al. [31]. ~~Sowing dates did not have an effect on the number of kernels per pod, seed index, and shelling percentage (Table 2).~~ Sowing dates did not have an effect on the number of kernels per pod, seed index, and shelling percentage (Table 2). However, numerically, the highest number of kernels per pod, seed index, and shelling percentage was observed when sown on May 15th, while the lowest values for these parameters were recorded for sowing on June 15th. Taller plants observed during early sowing periods may be attributed to the more ~~favorable~~favourable environmental conditions experienced by crops sown early, even when receiving similar inputs as those planted later. The reduced number of nodes and narrower internodal spaces resulting from suboptimal sowing times could also contribute to the decrease in plant height when sowing is delayed.

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3.2 Influence of planting density on yield attributes ~~throughout each year~~

The data also revealed significant effects of different planting densities on various parameters, as shown in Table 2. A planting density of 1.67 lac ha-1 resulted in the highest number of branches per plant, pegs per plant, pods per plant, kernels per pod, seed index, and shelling percentage, which was significantly greater than the results obtained with planting densities of 2.50 and 3.33 lac ha-1 (the kernels per pod and shelling percentage for planting densities of 2.50 and 3.33 lac ha-1 were statistically similar). As planting density increased up to 3.33 lac ha-1, there was a decrease in the number of branches per plant, pegs per plant, pods per plant, kernels per pod, seed index, and shelling percentage. This decrease could be attributed to heightened competition among plants for essential growth resources such as nutrients, water, and light as the number of plants per unit area increased. The optimal utilization of these resources at lower planting densities per unit area ultimately led to an increase in the number of branches per plant, pegs per plant, pods per plant, kernels per pod, seed index, and shelling percentage in groundnut. The choice of planting density should be carefully considered based on specific conditions and objectives. These studies collectively underline the importance of selecting the appropriate planting density to optimize groundnut yields, taking into account various environmental and regional factors. This reduction in weed competition was achieved through the smothering effect of groundnut on late-emerging weeds, which was more effective with narrow plant spacing compared to wider spacing. In the context of our study, the application of recommended double weeding likely contributed to increased yield by facilitating the efficient utilization of available resources when plants were optimally spaced. They suggested a medium planting density of 166,700 plants per hectare (60 cm × 20 cm with two plants per hill) and 200,000 plants per hectare (50 cm × 20 cm with two plants per hill) as optimal. These findings are consistent with earlier studies conducted by Sternitzke et al. [32], and Ahmad et al. [33]. Further, Ajeigbe et al. [27] reported that in Nigeria, pod yields were 31% higher when using a planting density of 133,333 hills per hectare (75 cm × 10 cm with two plants per hill) compared to 66,667 hills per hectare (75 cm × 20 cm with two plants per hill) and 40% higher compared to 44,444 hills per hectare (75 cm × 30 cm with two plants per hill). Similarly, in Ethiopia, it was found that planting densities of 250,000 plants per hectare (40 cm × 10 cm) and 200,000 plants per hectare (50 cm × 10 cm) were ideal for increasing seed yield in groundnut cultivars with different architectures [34]. In the Northern Guinea Savannah zone of Ghana, it was observed that the lowest sowing density of 80,000 plants per hectare resulted in the lowest pod and seed yields in groundnut, while medium (120,000 plants per hectare) and high (200,000 plants per hectare) sowing densities yielded higher pod and seed yields, with no significant difference between the latter two densities [35]. Sowing at a medium density enhanced pod yield by 8–10% compared to sowing at a low density. Additionally, crop simulation studies have suggested that increasing the plant density to 400,000 plants per hectare could significantly boost yields in areas of Africa where drought is not a limiting factor [36]. The results obtained for the rainy season appear to contradict those reported by Ajeigbe et al. [27], who found that increasing plant density to 133,333 hills per hectare (two plants per hill) resulted in a 14-22% increase in haulm yield compared to 44,444 hills per hectare (two plants per hill) and a 7-10% increase over 66,667 hills per hectare (two plants per hill) in the Sudanian agroecology of Nigeria. Many other studies have also reported that increasing plant spacing (wider spacing) leads to a higher number of pods per plant. For example, in Bangladesh, wider row and plant spacing were associated with a greater number of mature pods per plant and a higher dry weight of pods per plant [24]. This could be attributed to wider spacing allowing the plants to access more nutrients and solar energy while reducing competition for other resources. In Turkey, reducing plant density resulted in an increased number of pods and pod weight per plant, with specific planting densities (e.g., 70 cm × 25 cm and 75 cm × 25 cm) yielding the highest pod weight and pod number per plant for Virginia market types [25]. Similarly, in Sudan, increased plant density was linked to reduced seed yield per plant and a lower number of pods per plant due to increased competition in high-density plantings [37]. However, high-density planting produces pods of similar age and developmental stage, facilitating harvest decisions and positively impacting post-harvest processes such as shelling, sorting, and grain quality [38]. It's worth noting that while increasing plant density may lead to greater uniformity and potentially reduce weed growth due to canopy closure, it can also result in higher production costs for growers, including the need for more seeds and potentially increased labor costs [36]. The choice of planting density should be carefully considered based on specific conditions and objectives. These studies collectively underline the importance of selecting the appropriate planting density to optimize groundnut yields, taking into account various environmental and regional factors. Our findings emphasize the importance of tailoring planting densities and spacing to the specific characteristics of the groundnut variety and local agroecological conditions for optimal yield. These diverse findings underscore the importance of considering local agroecological conditions, rainfall patterns, and cultivar characteristics when determining the most suitable planting density and row spacing for groundnut cultivation to maximize yield potential.

3.3 The effect of the sowing date on crop yield

The haulm yield was significantly influenced by different sowing dates, as depicted in Table 3. Sowing on May 15th resulted in the highest haulm yield per hectare (5878.28 kg ha-1), which was markedly superior to yields obtained from other sowing dates. Haulm yield exhibited a decline as the sowing was delayed up to June 15th. Kernel and pod yield for groundnut displayed significant variations across different sowing dates (Table 3).

Table 3: Influence of various sowing dates and planting densities on groundnut yield and economic outcomes, considering the combined data from 2017 to 2019.

Treatments	kernel yield (kg ha^{-1})	Pod yield (kg ha^{-1})	Haulm yield (kg ha^{-1})	Harvest Index (%)	Net Return (ha^{-1})	B : C Ratio
Date of sowing						
Sowing at 15 May	2405.7 b	3370.6 b	5878.3 a	36.1c	105986 b	3.93 b
Sowing at 30 May	2791.2 a	3948.2 a	5543.7 b	41.5b	126232 a	4.68 a
Sowing at 15 June	2734.8 a	3895.1 a	5211.0 c	42.7a	124465 a	4.80 a
SEm±	40.9	53.7	28.9	0.28	2004	0.06
CD at 5%	121.5	159.5	86.1	0.82	5953	0.18
Planting density						
1.67 lac ha^{-1}	2473.5 b	3269.9 b	5361.9 c	37.7b	105701 b	4.49 b
2.50 lac ha^{-1}	2745.6 a	3971.1 a	5578.1 b	41.5a	127357 a	4.71 a
3.33 lac ha^{-1}	2712.6 a	3972.9 a	5692.9 a	41.1a	123625 a	4.21 c
SEm±	34.97	46.8	24.6	0.26	1746	0.05
CD at 5%	99.1	132.6	69.7	0.74	4951	0.15

Sowing on May 30th, while statistically similar to sowing on June 15th, recorded significantly higher kernel and pod yields compared to sowing on May 15th. Kernel and pod yields increased with delayed sowing from May 15th to May 30th, followed by a decrease in yields for sowing on June 15th. Sowing on June 15th resulted in the highest harvest index percentage, which was significantly superior to other sowing dates (Table 3). The harvest index exhibited an increase with delayed sowing from May 15th to June 15th. It's crucial to emphasize that groundnut performance exhibited variation across different sowing dates, with May 30th and June 15th sowings yielding superior results. The pronounced effect of sowing dates on various growth and yield parameters of groundnuts, including plant height, number of branches per plant, pegs per plant, pods per plant, and haulm dry weight, underscores the influence of environmental factors like temperature, daylight duration, and rainfall, which fluctuate with sowing dates, on groundnut performance. Similar findings were reported by [39]. Ramani et al. [40] similarly voiced this perspective, noting that early-sown crops tend to yield more seeds than late-sown crops. The significant effect of sowing dates on various growth and yield parameters of groundnuts, such as plant height, number of branches per plant, pegs per plant, pods per plant, and haulm dry weight, suggests that environmental factors like temperature, daylight duration, and rainfall, which vary with sowing dates, affect groundnut performance. This underscores the importance of selecting the appropriate sowing time to ensure optimal environmental conditions for improved yield parameters and ultimately, grain yield. The substantial yield increase observed in early sowing compared to delayed sowing dates could be attributed to the allocation of a larger proportion of total dry matter into various plant components. This highlights the significance of

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selecting the appropriate sowing time to ensure optimal environmental conditions for improved yield parameters and ultimately, grain yield.

3.4 The influence of planting density on crop yield

The data also showed that a planting density of 2.50 lac ha-1, along with a planting density of 3.33 lac ha-1, resulted in the highest kernel yield, pod yield, and harvest index for groundnut, and these two planting densities were statistically comparable (Table 3). In contrast, a planting density of 1.67 lac ha-1 yielded the lowest kernel and pod yield, as well as the lowest harvest index. This lower yield at the 1.67 lac ha-1 planting density can be attributed to the very low plant population. This lower yield at the 1.67 lac ha-1 planting density can be attributed to the very low plant population [41]. The higher harvest index associated with higher plant populations can be explained by the fact that while the yield per individual plant decreased with increased plant density, the total number of plants per hectare increased with higher planting density. Consequently, the kernel yield and pod yield per hectare increased with higher planting densities. These results align with previous studies by Rasekh et al. [31] and Kumawat et al. [42]. The higher harvest index associated with higher plant populations can be explained by the fact that while the yield per individual plant decreased with increased plant density, the total number of plants per hectare increased with higher planting density. Consequently, the kernel yield and pod yield per hectare increased with higher planting densities. Furthermore, haulm yield exhibited a significant increase with increasing planting density from 1.67 lac ha-1 to 3.33 lac ha-1 (Table 3). This increase in haulm yield may be attributed to the higher plant height and increased dry matter production per hectare, owing to the higher plant population per unit area. These findings are consistent with the research conducted by Jadhav et al. [43], Hirwe et al. [44], and Soumya et al. [45]. Various studies in different regions have highlighted the effect of planting density and row spacing on groundnut yield, Onat et al. [25] in Turkey observed that increasing plant density resulted in higher pod yield per hectare. In Pakistan, narrow-row planting with a spacing of 30 cm yielded significantly more (3739 kg/ha) compared to wide-row planting with a spacing of 60 cm (1903 kg/ha) [33]. Research in Vietnam found that plant densities and row spacing of 350,000 plants per hectare (25 cm × 25 cm with two plants per hill) and 400,000 plants per hectare (25 cm × 20 cm with two plants per hill) were suitable for achieving high yields [26]. In Australia, Bell et al. [46] reported an increase in total dry matter and pod yields with increasing plant density under fully irrigated conditions. Different cultivars showed varying responses, with the best cultivar (chico) achieving the highest total dry matter and pod yields at a density of 352,000 plants per hectare. These findings are consistent with Wright and Bell [47] and Kaushik et al. [41], who also observed that increased inter-row spacing led to higher pod yield per hectare. However, the results from Dapaah et al. [48] indicated a different outcome during drier seasons in 2009. They found that the highest plant density of 333,000 plants per hectare increased pod yield by 29 to 46% and seed yield by 28 to 44% compared to lower plant densities. This suggests that in drier seasons, higher plant density might provide an advantage in moisture conservation, especially once crop canopy closure is achieved. Ojelade et al. [49] attributed the enhanced growth and yield of groundnut with narrow intra-row spacing to reduced competition from weeds for vital resources like light, nutrients, space, and water. This reduction in weed competition was achieved through the smothering effect of groundnut on late-emerging weeds, which was more effective with narrow plant spacing compared to wider spacing. In the context of our study, the application of recommended double weeding likely contributed to increased yield by facilitating the efficient utilization of available resources when plants were optimally spaced. However, Dapaah et al. [48] recommended different planting densities under favorable conditions in the forest-savannah transitional agroecological zone of Ghana. They suggested a medium planting density of 166,700 plants per hectare (60 cm × 20 cm with two plants per hill) and 200,000 plants per hectare (50 cm × 20 cm with two plants per hill) as optimal. In Bangladesh, research indicated that the optimal spacing for maximum yield varied depending on groundnut variety. Erect (bunch) groundnut varieties were found to perform best with narrower spacing (30 cm × 10 cm), while spreading or semi-spreading groundnut varieties required wider spacing (40 cm × 20 cm) to achieve their full yield potential [24]. These findings emphasize the importance of tailoring planting densities and spacing to the specific characteristics of the groundnut variety and local agroecological conditions for optimal yield. These diverse findings underscore the importance of considering local agroecological conditions, rainfall patterns, and cultivar characteristics when determining the most suitable planting density and row spacing for groundnut cultivation to maximize yield potential. Moreover, interaction between sowing dates and planting density was notably significant, especially in relation to pod yield and kernel yield (as shown in Table 4 and represented in Figure 1, 2, and 3).

Table 4: The combined effect of sowing date and planting density on groundnut yield (kg/ha), considering the pooled data from 2017 to 2019.

Treatments	Pod yield (kg ha^{-1})			Kernel yield (kg ha^{-1})			Haulm yield (kg ha^{-1})		
	Sowing at 15 May	Sowing at 30 May	Sowing at 15 June	Sowing at 15 May	Sowing at 30 May	Sowing at 15 June	Sowing at 15 May	Sowing at 30 May	Sowing at 15 June
Planting density									
1.67 lac ha^{-1}	2717.0	3575.7	3517.3	2075.9 d	2702.2 b	2642.4 b	5561.9	5432.9	5090.9
2.50 lac ha^{-1}	3451.4	4235.1	4226.8	2403.8 c	2921.6 a	2911.5 a	5887.8	5577.3	5269.3
3.33 lac ha^{-1}	3943.5	4033.9	3941.2	2737.6 b	2749.7 b	2650.5 b	6185.2	5620.8	5272.7
SEm±	81.03			60.56			42.58		
CD at 5%	229.76			171.71			120.73		

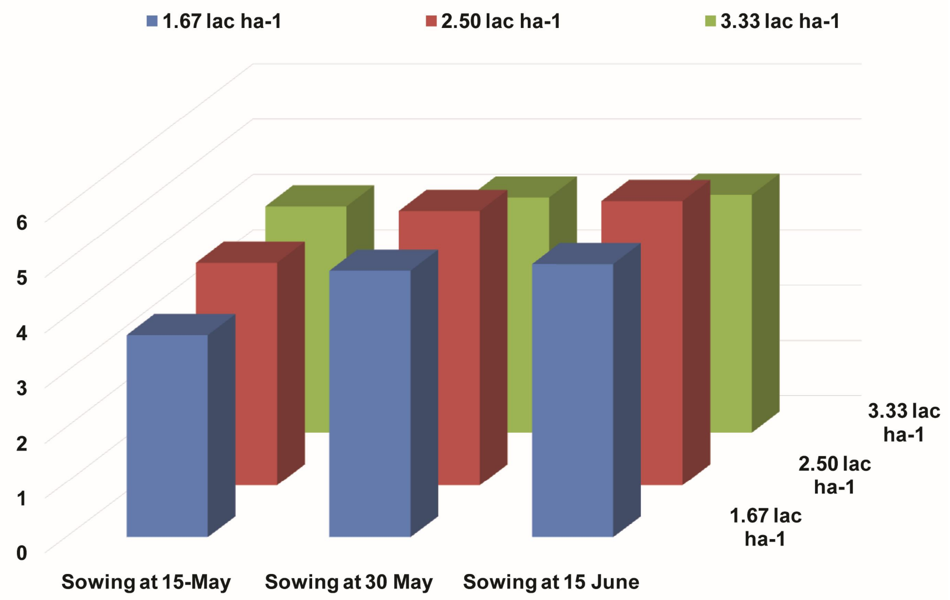

Figure 2: The combined effect of sowing date and planting density on groundnut pod yield (kg/ha) for the pooled years 2017-2019.

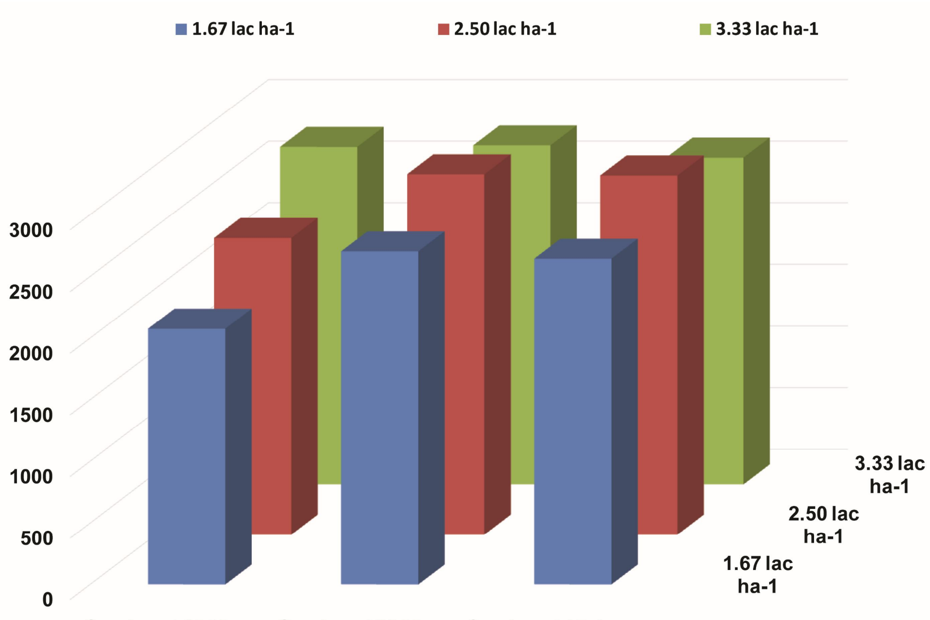

Figure 3: The synergistic influence of sowing date and planting density on groundnut kernel yield (kg/ha) across the collective years of 2017 to 2019.

3.5 The combined influence of sowing dates and planting density on crop yield

The interaction effect between sowing dates and planting density was found to be significant, particularly concerning pod yield and kernel yield (Table 4 and Figure 1, 2, and 3). The highest pod yield and kernel yield were recorded when the planting density was 2.50 lac ha-1, regardless of whether sowing was done on May 30th or June 15th. However, when sowing occurred on May 15th, the highest haulm yield was obtained with a planting density of 3.33 lac ha-1. Increasing planting density significantly increased pod yield, kernel yield, and haulm yield when sowing took place from May 15th to May 30th, up to a planting density of 3.33 lac ha-1. However, for groundnut sown on May 30th and June 15th, the optimal planting density was 2.50 lac ha-1. Optimal plant population densities also have a positive effect on growth hormones such as auxins and their interaction with light [50]. These optimal plant populations are particularly beneficial in favorable environmental conditions, contributing to optimized growth and yield parameters in short-season production systems. Further, variations in environmental factors such as temperature and rainfall during different growth periods, interacting with plant density, may have played a role in differences in crop phenology. These findings are consistent with the research conducted by Giayetto et al. [51] and Rasekh et al. [31]. A strong association between the mean photosynthetically active radiation (PQ) and the number of pods and seeds in pea, which is another leguminous crop [52]. It was also reported that variations in haulm yield associated with different sowing dates. The increased yield attributes observed during early sowing dates likely played a role in achieving a higher harvest index. This outcome can be attributed to the more efficient partitioning of produced dry matter, resulting in a greater grain yield. Billore et al. [53] similarly noted that early sowing led to higher yields, which they attributed to the elevated values of the harvest index in soybean. Furthermore, Bagnall and King [14, 15] highlighted a significant reduction in dry matter production due to the low irradiance levels. The taller plants observed at a planting density of 3.33 lac ha-1 can be attributed to increased competition among crops to intercept radiation. Moreover, plants at higher densities tend to allocate more resources to stem growth at the expense of reproductive tissue, ultimately resulting in increased haulm yield. It was also reported that variations in haulm yield associated with different sowing dates. The increased yield attributes observed during early sowing dates likely played a role in achieving a higher harvest index. ~~This outcome can be attributed to the more efficient partitioning of produced dry matter, resulting in a greater grain yield.~~

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3.6 The effect of sowing date on the Benefit-to-Cost (B,C) ratio

The net return and benefit-to-cost (B,C) ratio of groundnut exhibited significant differences among various sowing dates (Table 3). Sowing on May 30th, while statistically similar to sowing on June 15th, resulted in significantly higher net returns and B,C ratios compared to sowing on May 15th. This difference in profitability can be attributed to the increased pod and haulm yield of the groundnut crop, which was more pronounced in the treatment where sowing occurred on May 30th. Halvankar et al. [54] reported an increase in test weight associated with early sowing. Further, early sowing demonstrated higher gross returns, net returns, and B, C ratios compared to delayed sowing. Among the various sowing dates, June 28th sowing resulted in the highest gross returns, net returns, and B, C ratio, surpassing the results of July 14th and July 29th sowings in soybean [55].

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3.7 The influence of planting density on the Benefit-to-Cost (B,C) ratio

There were significant differences in net returns among various planting densities for groundnut. Planting densities of 2.50 lac ha-1 and 3.33 lac ha-1, while statistically similar to each other, resulted in significantly higher net returns compared to a planting density of 1.67 lac ha-1 (Table 3). Similarly, the Benefit-to-Cost (B,C) ratio of groundnut varied significantly with different planting densities. A planting density of 2.50 lac ha-1 yielded a significantly higher B,C ratio compared to planting densities of 1.67 lac ha-1 and 3.33 lac ha-1. This difference in profitability can be attributed to the increased pod and haulm yield of the groundnut crop, which was more pronounced in the treatment with a planting density of 2.50 lac ha-1. Despite the fact that all the yield-related characteristics exhibited better performance at wider spacings, these enhancements were not adequate to offset the yields achieved through a higher plant population per unit area resulting from closer spacing. Rajput and Kaushik [56] also reported a greater number of seed pods per plant at lower plant densities. Despite the fact that all the yield-related characteristics exhibited better performance at wider spacings, these enhancements were not adequate to offset the yields achieved through a higher plant population per unit area resulting from closer spacing. This increase in seed yield at closer spacings corresponds with the findings reported by Manjappa et al. [57] and Sundari [58]. Moreover, the interaction effect between the sowing date and planting density was found to be significant, particularly concerning economic parameters (as shown in Table 5 and depicted in Figure 4 and 5).

Table 5: The interplay between sowing date and planting density's influence on the Net Return and Benefit-to-Cost (B:C) Ratio of groundnut, utilizing the pooled data from 2017 to 2019.

Treatments	**Net Return (Rs ha^{-1})**			**B : C Ratio**		
	Sowing at 15 May	**Sowing at 30 May**	**Sowing at 15 June**	**Sowing at 15 May**	**Sowing at 30 May**	**Sowing at 15 June**
Planting density						
1.67 lac ha^{-1}	85564	116867	114672	3.67	4.83	4.95b
2.50 lac ha^{-1}	108829	136640a	136602a	4.02	4.96b	5.14a
3.33 lac ha^{-1}	123566b	125189b	122121b	4.09	4.25	4.30
SEm±	3024.41			0.09		
CD at 5%	8575.20			0.26		

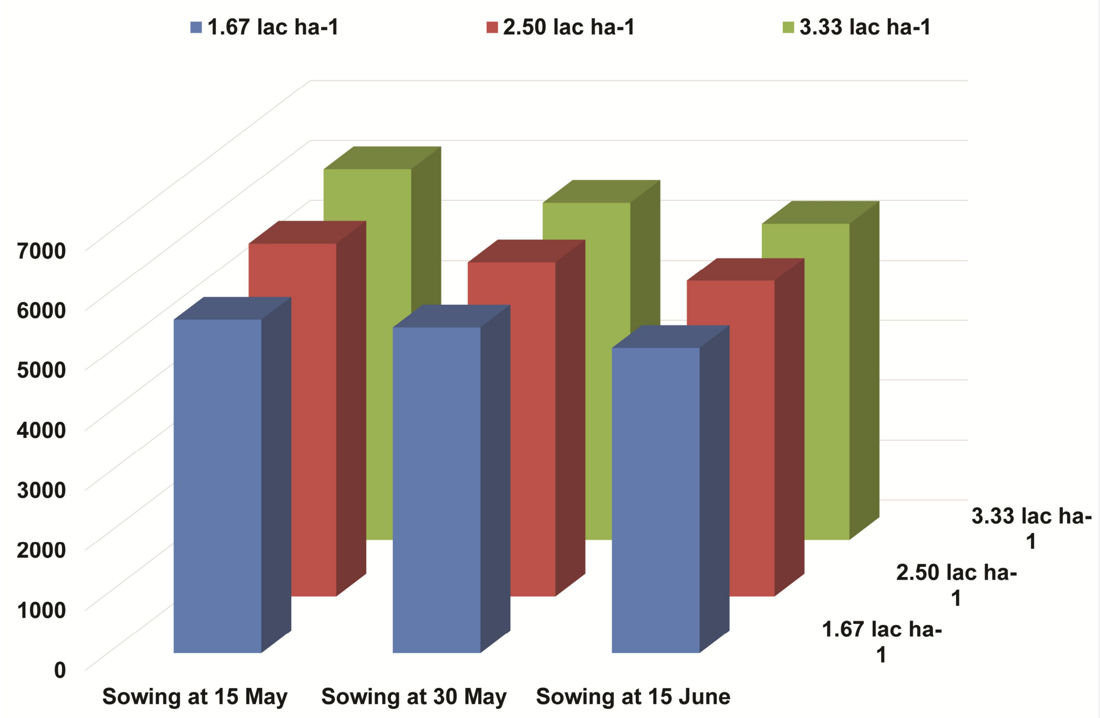

Figure 4: The combined effect of sowing date and planting density on groundnut haulm yield (kg/ha), taking into account the years 2017 to 2019.

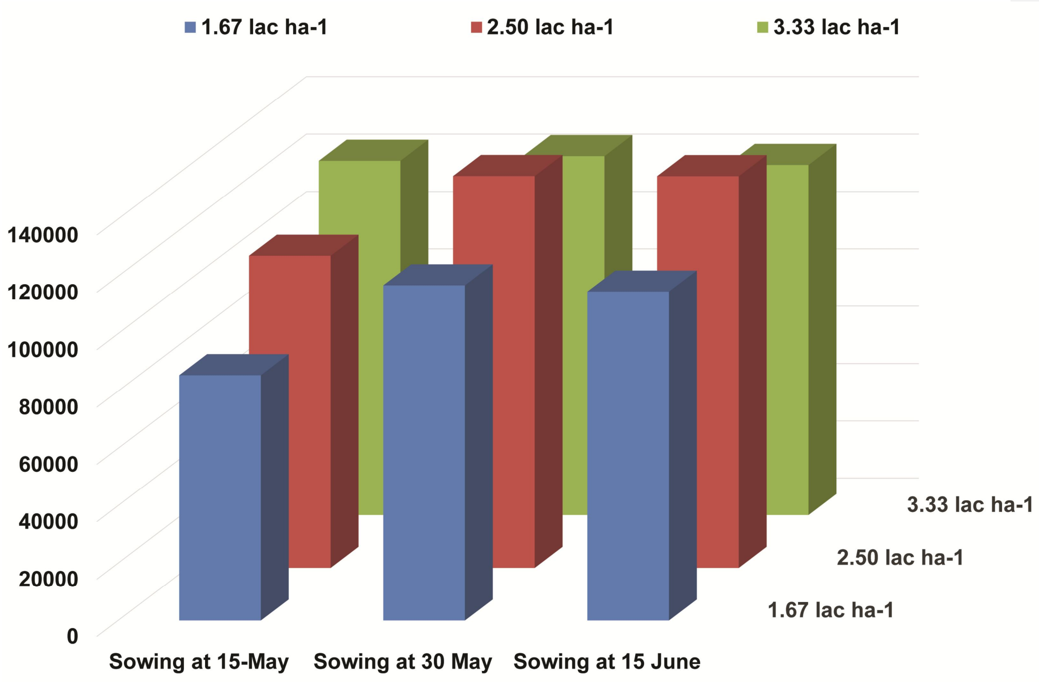

Figure 5: The combined effect of sowing date and planting density on groundnut's net returns (Rs/ha), considering the years 2017 to 2019.

3.8 The combined influence and interaction effects of sowing dates and planting density on the Benefit-to-Cost (B,C) ratio

The interaction effect between the sowing date and planting density was found to be significant, particularly concerning economic parameters (as shown in Table 5 and depicted in Figure 4 and 5). The highest net return and Benefit- ~~to-~~Cost (B:~~,~~C) ratio were recorded when the planting density was 2.50 lac ha-1, regardless of whether sowing was done on May 30th or June 15th. However, for groundnut sown on May 15th, the optimal net return was achieved with planting densities ranging from 1.67 lac to 3.33 lac ha-1. The increasing planting density significantly increased net returns up to a planting density range of 1.67 lac to 3.33 lac ha-1 when sowing was conducted on May 15th. (Figure 6).

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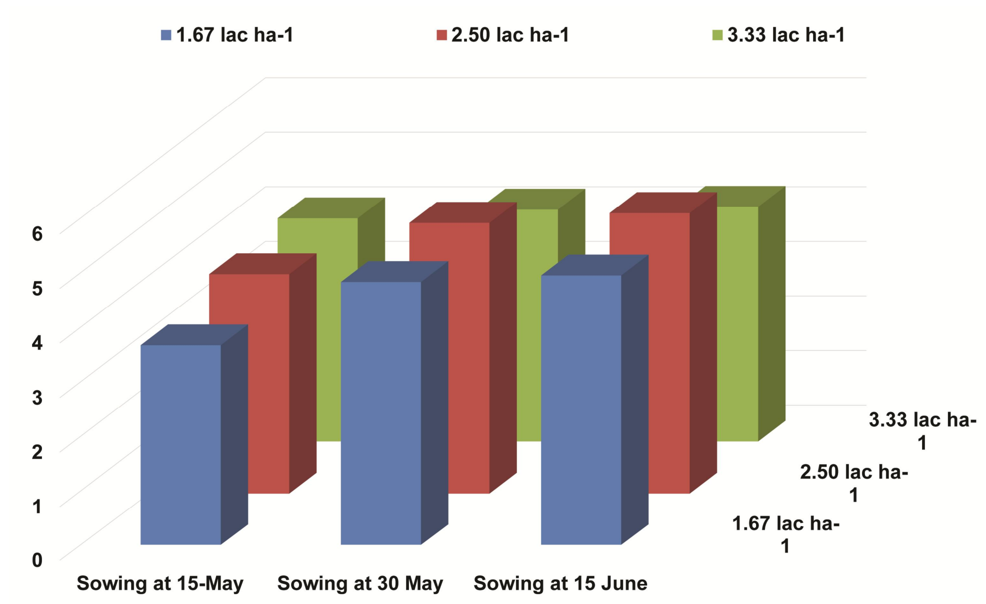

Figure 6: The interplay between sowing date and planting density's influence on the Benefit~~-to-~~Cost Ratio (B:C) ~~Ratio~~ of groundnut (Rs/ha), aggregated for the years 2017 to 2019.

However, for groundnut sown on May 30th and June 15th, the net return was maximized at a planting density of 2.50 lac ha-1. These disparities in crop performance and economic outcomes can be attributed to variations in environmental factors, including temperature and rainfall during different growth periods, which interacted with plant density and influenced crop phenology. These findings align with previous research conducted by [51] and [31]. The positive correlation observed between narrower plant spacing and increased plant height can be ascribed to heightened inter-plant competition. This competition leads to internodal elongation, a phenomenon that has been documented ~~by - [54]~~ in soybean [54]. Arnon ~~[59]~~ suggested that there is a linear increase in dry matter yield with higher plant density across various crops [59]. Collectively, these findings demonstrated that the timing of sowing and the choice of planting density emerge as crucial factors for enhancing groundnut productivity in this specific region, particularly in light of the evolving climate conditions.

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4. CONCLUSION

Groundnut holds immense significance as an oilseed crop on a global scale. The growth and development of plants, along with crop productivity, are substantially impacted by the adverse effects of global climate change. In this work, we investigated the effects of distinct sowing dates and planting densities on the yield and economic aspects of groundnut in the hot arid region of Rajasthan, India. Remarkably, the diverse sowing dates and planting densities exhibited notable effects on groundnut's yield components, overall yield, and economic viability. Comparative analysis revealed that sowing on May 30th, while statistically comparable to June 15th sowing, yielded the highest number of branches, pegs, pods per plant, kernel and pod yield, net return, and benefit-cost ratio. Interestingly, the highest haulm yield per hectare was achieved with the May 15th sowing, yet the harvest index improved progressively as sowing was delayed from May 15th to June 15th. Furthermore, utilizing a planting density of 1.67 lakh plants per hectare yielded the maximum numbers of branches, pegs, pods, kernels per pod, seed index, and shelling percentage. Conversely, a planting density of 3.33 lakh plants per hectare maximized haulm yield. In an intriguing interplay between sowing dates and plant populations, the most ~~favorable~~favourable pod yield, kernel yield, and net return were achieved with a planting density of 2.50 lakh plants per hectare for the May 30th sowing. These findings underscore the substantial effect of sowing date and planting density on yield-related characteristics, ultimately influencing groundnut yield in the challenging hot arid region. Hence, the timing of sowing and the

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choice of planting density play pivotal roles in amplifying groundnut productivity within this specific region, especially considering the changing climate conditions.

However, further research, including breeding and management studies, should be undertaken to maximize the yield and profitability of groundnut production in such environments. Breeding programs aimed at developing early maturing, high-yielding groundnut cultivars are necessary to tap into the crop's full yield potential. Additionally, the cultivation of heat-tolerant cultivars can be advantageous for early sowing. Agronomic practices such as mulching and ridge sowing should also be explored to enhance early crop development.

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INSTITUTIONAL REVIEW BOARD STATEMENT

Not applicable.

INFORMED CONSENT STATEMENT

Not applicable.

DATA AVAILABILITY STATEMENT

Data is available in the manuscript.

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