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ARAŞTIRMA MAKALESİ **RESEARCH ARTICLE**

Impact of Different Plant Development Regulators on Yield Components and Growth in Peanut

Yerfıstığında Farklı Bitki Gelişim Düzenleyicilerinin Verim Bileşenleri ve Büyüme Üzerine Etkisi

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Abstract

Plant growth regulators (PGRs) are organic compounds, produced within the plant or applied exogenously, that regulate physiological processes. These substances are active at low concentrations, can be translocated to other organs, and may exert either promotive or inhibitory effects on growth. This study aimed to determine the effects of PGRs, applied at different doses and developmental stages, on selected agronomic traits of groundnut (*Arachis hypogaea* L.). The research was conducted in Osmaniye province, situated in the Eastern Mediterranean Transition Zone, during the 2019 and 2020 main crop seasons. The experiment was arranged in a randomized complete block design (RCBD) with three replications. The experimental treatments consisted of the following: GA_3BB10, GA_3BB20, GA_3FB10, GA_3FB20, SWBB40, SWFB60, SWBBFB100, MCBB150, MCBB200, MCFB150, MCFB200, and a Control. A range of agronomic and quality parameters was assessed, including leaf length and width, the number of leaves and branches per plant, plant height, the number of pods per plant, pod weight per plant, 100-pod weight, 100-seed weight, shelling percentage, protein content, and pod yield. The findings of the study revealed that the application of treatments exerted a statistically significant influence on all measured traits, with the exception of the number of branches per plant. The GA_3FB20 treatment yielded the highest values for shelling percentage (76.27%) and pod yield (669.76 kg da^{-1}), whereas the MCBB200 treatment resulted in the superior protein content (26.90%). Principal component analysis (PCA) indicated that the first three principal components (PCs) accounted for 80.369% of the total observed variance. In the biplot generated from PC1 and PC2, the GA_3FB20, GA_3FB10, and GA_3BB20 treatments were identified in closer proximity to the vector for pod yield, suggesting a stronger association with this key parameter. In conclusion, it was determined that plant growth regulators had positive effects on the yield and yield components of the peanut plant, and in terms of pod yield, the application of GA_3 at 20 ppm, particularly during the full blooming period, was appropriate.

Keywords: Gibberellic acid, Seaweed, Mepiquat-chloride, Peanut (*Arachis hypogaea* L.), Pod yield

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Öz

Bitki büyüme düzenleyiciler, bitkiler tarafından oluşturulan veya bitkilere dışarıdan verilen, çok düşük dozlarda dahi bitkideki fizyolojik olayları olumlu ya da olumsuz etkileyen, diğer bitki kısımlarına taşınabilen ve bu etkinliğini diğer organlarda da devam ettirebilen organik maddelerdir. Bitki gelişimini teşvik ettikleri gibi engelleyici rolleri de bulunmaktadır. Bu çalışmada, farklı gelişim dönemlerinde farklı dozlarda uygulanan bitki büyüme düzenleyicilerin yerfıstığı bitkisinin (*Arachis hypogaea* L.) bazı agronomik özellikleri üzerindeki etkisini incelemek amaçlanmıştır. Araştırma, 2019 ve 2020 yıllarında ana ürün koşullarında, Doğu Akdeniz Geçit Kuşağı bölgesinde bulunan Osmaniye ilinde yürütülmüştür. Deneme, tesadüf bloklar deneme desenine (RCBD) göre üç yinelemeli olacak şekilde dizayn edilmiştir. Denemede: GA_3BB10, GA_3BB20, GA_3FB10, GA_3FB20, SWBB40, SWFB60, SWBBFB100, MCBB150, MCBB200, MCFB150, MCFB200 ve Kontrol olmak üzere toplamda on iki farklı uygulama yapılmıştır. Yürütülen çalışmada yaprak boyu, yaprak eni, bitki başına yaprak sayısı, bitki boyu, bitki başına dal sayısı, bitki başına meyve sayısı, bitki başına meyve ağırlığı, 100 meyve ve tohum ağırlığı, kabuk iç oranı, protein içeriği ve meyve verimi gibi parametreler incelenmiştir. Araştırma sonucunda, uygulamaların bitki başına dal sayısı hariç incelenen özellikler üzerinde istatistiki olarak önemli etkisi bulunduğu tespit edilmiştir. En yüksek kabuk iç oranı (%76.27) ve meyve verimi (669.76 kg da^{-1}) GA_3FB20 uygulamasından elde edilirken, protein oranı açısından MCBB200 uygulaması %26.90 değeriyle ön plana çıkmıştır. Yapılan temel bileşen analizi (PCA) sonucuna göre, ilk üç temel bileşenin (PC) toplam varyansı %80.369 oranında açıkladığı belirlenmiştir. PC1 ve PC2 baz alınarak oluşturulan grafikte, GA_3FB20, GA_3FB10 ve GA_3BB20 uygulamalarının meyve verimine daha yakın konumda bulunduğu görülmüştür. Sonuç olarak, bitki büyüme düzenleyicilerin yerfıstığı bitkisinin verim ve verim unsurları üzerine olumlu etkileri olduğu, meyve verimi açısından GA_3 uygulamasının özellikle tam çiçeklenme döneminde 20 ppm olarak verilmesinin uygun olduğu sonucuna varılmıştır.

Anahtar Kelimeler: Gibberellik asit, Deniz yosunu, Mepiquat klorür, Yerfıstığı (*Arachis hypogaea* L.), Meyve verimi

1. Introduction

Peanut, a legume, is a significant oil plant in both human and animal nutrition due to its high fat and protein content (Onemli, 2005; Killi and Beycioglu, 2022; Yilmaz et al., 2023). Peanut seeds, which are widely grown in India, China, and the United States, comprise 20-35% protein and 45-55% oil (Baran and Andırman, 2022). Peanut seeds are a plant high in saturated fat and unsaturated fatty acids, with 15-43% linoleic acid and 36-67% oleic acid (Gulten et al., 2023).

The world population is increasing rapidly, and there is a need to inrement the productivity of plants so that meet the food needs of this rapidly increasing population (Erdemli and Kaya, 2015; Ballesteros et al., 2024). So that rise the quality and productivity of plants, it is crucial to develop high-yield varieties that perform well in different environmental conditions, as well as to use advanced cultivation techniques (Erdemli and Kaya, 2015).

Gibberellic acid, a natural plant growth regulator (PGR), helps it grow by stimulating cell division and increasing the plastids in the cell walls (Khan et al., 2024). It converts carbohydrates into sugar and reduces the pressure on the cell wall. Thus, as water is taken into the cell, it allows the cell to elongate. (Erdemli and Kaya, 2015). Gibberellic acid plays a significant role in seed germination, growth of vegetative organs, and reproductive development (Khan and Chaudhry, 2006; Heydari et al., 2021).

Plant growth regulators such as seaweed are widely used to reduce the harmful effects of stress caused by poor environmental conditions on plants (Behradfar et al., 2015). Seaweed is one of eight main types of biostimulants that, when applied foliarly, have significantly increased the stress tolerance of a wide range of crops, including cereals, flowers, grasses, and different vegetables (Mannan et al., 2023). Seaweed has a variety of minerals, including P, Ca, Mg, and Fe, which are essential for plant nutrition. It also contains secondary metabolites and other biochemicals that benefit plants, such as enhanced yield (Rouphael and Colla, 2020).

Mepiquat-chloride, one of the PGRs, increased the quality and yield by increasing photosynthesis (Srikala et al., 2023). Mepiquat-chloride, a gibberellin acid inhibitor, prevents excessive plant height in plants by inhibiting cell elongation (Yenikalaycı and Arslan, 2023). Mepiquat chloride is a common PGR used in cotton and other plants to slow down vegetative growth, boost production, and enhance the quality of the fiber (Tung et al., 2018).

As in all plants, it is important to ensure high quality yield increase in the plant as well as high yield increase per unit area in peanuts. Therefore, different PGRs (mepiquat-chloride, seaweed, gibberellic acid) were used in peanuts at different doses and times and their effects on quality and yield were examined.

2. Materials and Methods

2.1. Materials

The peanut variety NC 7, which is a participant in the Virginia market type and has a semi-spreading growth form, was used as a plant material. It has a growing phase of roughly 140-160 days. NC 7 pod kernel color is yellowish, while the seed testa color is light pink, cylindrical, and large. Seaweed (SW), Gibberellic acid (GA_3), and mepiquat-chloride (MC)) were among the several compounds utilized in a total of twelve treatments at three distinct development stages (full bloom (FB), beginning bloom (BB), and beginning bloom + full bloom (BB+FB). The treatment doses and treatment times were given in *Table 1*.

Table 1. Abbreviations, growth regulators, application periods, and doses of the experimental treatments

Abbreviation	Growth Regulator	Period and Dose
GA_3BB10	Giberallic Acid	Beginning Bloom – 10 ppm
GA_3BB20	Giberallic Acid	Beginning Bloom – 20 ppm
GA_3FB10	Giberallic Acid	Full Bloom – 10 ppm
GA_3FB20	Giberallic Acid	Full Bloom – 20 ppm
SWBB40	Seaweed	Beginning Bloom – 40 ppm
SWFB60	Seaweed	Full Bloom – 60 ppm
SWBBFB100	Seaweed	Beginning Bloom + Full Bloom – 100 ppm
MCBB150	Mepiquat-Chloride	Beginning Bloom – 150 ppm
MCBB200	Mepiquat-Chloride	Beginning Bloom – 200 ppm
MCFB150	Mepiquat-Chloride	Full Bloom – 150 ppm
MCFB200	Mepiquat-Chloride	Full Bloom – 200 ppm
Control	---	---

2.2. Experimental site

Experiments were ruled at Oil Seed Research Institute in Osmaniye (37º07'40.51"N; 36º12'02.08"E, and 69 m) in Türkiye during the 2019 and 2020 growing seasons. The soil of experimental area was classified as clay which contained average pH 8.4. Organic matter, nitrogen, phosphorus, and potassium levels were low, however lime and iron levels were average. The climatic information taken from Osmaniye State Meteorology Institute. Regarding average temperatures, there were no appreciable variations between the long year and the examined years. The overall rain in 2020 was comparable to the long year (266.50 mm), but in 2019 it was rather lower (193.80 mm) when comfront to other information (*Figure 1*).

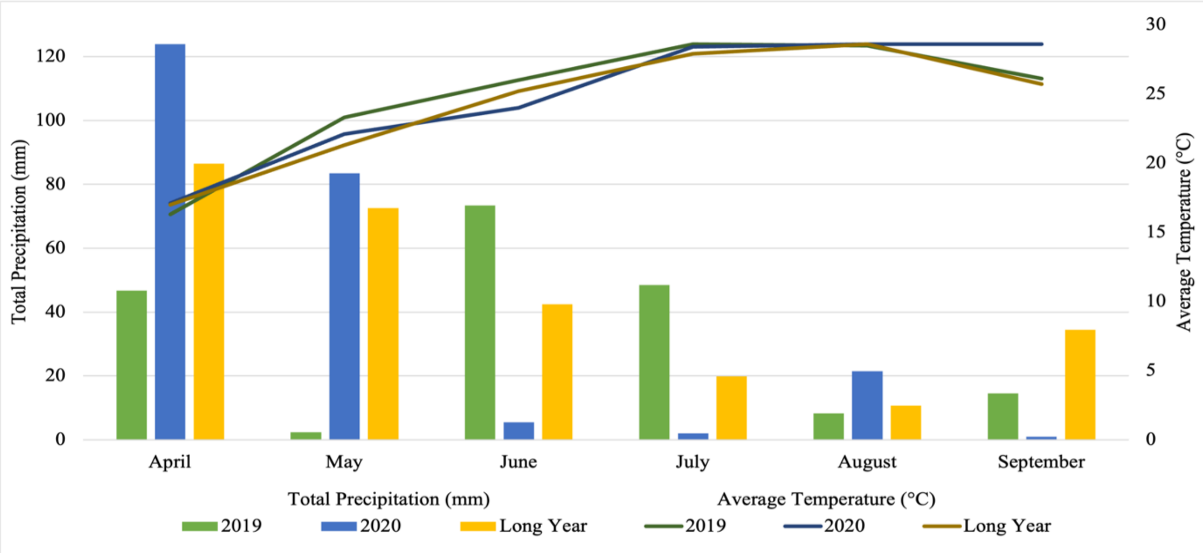

Figure 1. Climate parameters of the research field (2019, 2020, and long-year average)

2.3. Methods

The experiments were implemented using a randomized complete block design (RCBD) with three replications. The seeds were manually planted in four-row, five-meter rows with 70 centimeters between rows and 15 centimeters inside in both years. Before sowing, 25 kg da^{-1} di-ammonium phosphate (18% N, 46% P_2O_5) fertilizer was applied (Asik et al., 2018). On May 5, 2019, manually planted in the experiment's first year. PGR was sprayed as beginning bloom treatment in the first year on June 17, 2019, and full bloom treatment was performed on June 27, 2019. On September 28, 2019, the plants that had attained harvest maturity were manually harvested. On May 2, 2020, manually planted in the experiment's first year. PGR was sprayed as beginning bloom treatment in the first year on June 13, 2020, and full bloom treatment was performed on June 24, 2020. On September 21, 2020, the plants that had reached harvest maturity were manually harvested. The PGR_S dosages were computed based on previous research and managed to plant leaves using a spraying machine (Osman and Salem, 2011; Saini and Jain, 2017).

All of the plants in the parcel were harvested to calculate the pod yield. Twenty plants were chosen from the experiment's center two rows provided seed samples for the other attributes. Number of pods per plant (no plant^{-1}), pods weight per plant (g), 100-pod weight (g), shelling percentage (%), 100-seed weight (g), pod yield (kg da^{-1}), and protein content (%) were measured and calculated according to Asik et al. (2018). Besides, the leaf-related measurements, such as leaf width (cm), leaf size (cm), and number of leaves (no plant^{-1}), and the number of branches per plant with plant height (cm) were determined (Dapaah et al., 2014; Awal and Aktar, 2015; Ribeiro et al., 2022).

2.4. Statistical analyses

The Randomized Complete Block Design (RCBD) with joined years was applied to the experimental data using SPSS v22 for the analysis of variance. Prior to combining the years, Bartlett's test was performed on all examined characteristics to verify homogeneity of variances between years. The test confirmed variance homogeneity across all parameters, justifying the data combination. The Duncan multiple range test was utilized to compare the means. Both the principal component analysis and its graphical representations were prepared using JMP Pro 17.0.0.

3. Results and Discussion

3.1. Effects of PGR on leaf size, leaf width, number of leaves, and plant height of peanut

The combined analysis of variance for both years indicated a statistically significant effect of the treatments on leaf size and leaf width ($p < 0.01$) (*Table 2*). In the applications, leaf size varied between 3.30 cm and 4.13 cm. The GA_3 applied at full blooming with 10 ppm (GA_3FB10) came to the forefront with its value, followed by the other GA_3 and mepiquat-chloride treatments. The measured leaf width values ranged from 1.58 cm to 1.95 cm. Among the treatments, the greatest leaf width measurements were associated with the GA_3FB20 (1.95 cm) and MCBB200 (1.94 cm) applications (*Table 3*). This observation is consistent with the role of gibberellic acid in promoting cell elongation and leaf expansion. Leite et al. (2003) reported that gibberellic acid applications increased the leaf area index in soybean (*Glycine max* L.). Hossain et al. (2023) determined that gibberellic acid applications increased the leaf area of papaya (*Carica papaya* L.) and that the leaf area varied based on the time and dose of gibberellic acid treatment. Tung et al. (2023) in cotton (*Gossypium hirsitum* L.) recorded that gibberellic acid applications decreased the leaf area index. Chaudhari et al. (2023) in peanut found that mepiquat chloride applications reduced leaf area and leaf area index. Banon et al. (2023) in sage (*Salvia officinalis* L.) determined that mepiquat chloride applications reduced leaf area. The variability in the literature underscores the context-dependent nature of PGR effects. In our study, the applications that produced the greatest leaf dimensions (GA_3FB10 for length, GA_3FB20 and MCBB200 for width) were all timed during the blooming period. This leads us to suggest that the peanut plant's leaf expansion may be particularly responsive to PGRs at this reproductive stage. The fact that mepiquat chloride (MCBB200) did not reduce leaf width but was among the top performers is particularly interesting. It is plausible that, in peanut, a moderate application of this compound at beginning bloom may optimize canopy architecture without curtailing leaf growth, potentially benefiting subsequent pod development. Therefore, while not all PGRs statistically outperformed the control, the observed trends point to the blooming period as a critical window for managing leaf traits with specific regulators.

Table 2 Results of the analysis of variance for characteristics studied in the experiment

	Year(df=1)	Block (df=4)	Treatments (df=18)	Y × T (df=18)
Leaf Size	ns	ns	**	ns
Leaf Width	ns	ns	**	**
Number of Leaves	ns	ns	**	ns
Plant Height	ns	ns	**	ns
Number of Branches	**	ns	ns	ns
Number of Pods Per Plant	**	ns	**	ns
Pod Weight Per Plant	**	ns	**	**
100-Pod Weight	**	ns	**	ns
100-Seed Weight	**	ns	**	ns
Shelling Percentage	ns	ns	**	ns
Protein Content	ns	ns	**	ns
Pod Yield	**	ns	**	**

df: Degree of freedom; ns: Non-significant; ** $p < 0.01$

A statistically significant difference was observed among the treatments for the number of leaves per plant ($p < 0.01$) (*Table 2*). The highest number of leaves was recorded in the GA_3BB10 (1075.00 leaves plant^{-1}) and MCFB150 (1057.83 leaves plant^{-1}) applications, whereas the lowest values were found in the GA_3FB10 (666.66 leaves plant^{-1}) and SWBB40 (672.83 leaves plant^{-1}) applications (*Table 3*). This striking contrast, where the same regulator (GA_3) applied at different times (GA_3BB10 vs. GA3FB10) produced both the highest and one of the lowest leaf counts, highlights the critical importance of application timing. The literature provides a context for these results. The promoting effect of gibberellic acid on leaf number, as seen in our GA_3BB10 treatment, aligns with findings in peanut (Faldu et al., 2018) and papaya (Hossain et al., 2023). Similarly, the positive effect of seaweed extract observed in other species (Habashy and Bishara, 2013; Elansary et al., 2016) offers a basis for understanding the performance of certain treatments in our study. Conversely, the result for MCFB150 (mepiquat chloride at full bloom) appears contradictory to reports of its growth-retarding effects (Banon et al., 2023). Interpretation of these findings indicated that the effect of a PGR on leaf number in peanut was not inherent to the compound alone but was decisively modulated by its application stage. The substantial difference between GA_3BB10 and GA_3FB10 suggested that GA_3 application at the beginning of bloom stimulated vegetative growth and leaf production more effectively than application at full bloom. The favorable result with MCFB150, on the other hand, implied that the action of mepiquat chloride in peanut might be complex, potentially regulating plant architecture without suppressing leaf initiation when applied at specific reproductive stages. These outcomes underscored the critical importance of application timing in achieving targeted physiological responses with PGRs in peanut cultivation.

The combined analysis of variance for the two years indicated statistically significant differences in plant height among the treatments ($p < 0.01$) (*Table 2*). The measured plant height values ranged from 31.73 cm to 40.66 cm (*Table 3*). Among the applications, those resulting in the greatest plant height measurements were GA_3BB20 (40.66 cm), MCBB200 (38.60 cm), and MCFB200 (38.36 cm). In contrast, the applications associated with the most reduced plant height were SWFB60 (31.73 cm) and the Control (32.80 cm). The literature provides a framework for understanding these observations. The association of greater plant height with gibberellic acid (GA_3) applications, particularly GA_3BB20, is consistent with numerous studies in legumes and other crops (Faldu et al., 2018; Patil, 2019; Leite et al., 2003). Similarly, the favorable performance of some mepiquat chloride treatments (MCBB200, MCFB200) contrasts with its typical role as a growth retardant (Kim et al., 2011), suggesting a dose- and stage-specific response in peanut. The result for SWFB60, which was among the most reduced in height, indicates that the effect of seaweed extract may also be highly dependent on application parameters. These results demonstrated that plant height in peanut was a highly responsive trait to PGR management. The linkage of the most pronounced height to a GA_3 application at the beginning bloom (GA_3BB20) pointed to the early reproductive phase as a key window for influencing stem elongation. Conversely, the outcome where specific mepiquat chloride treatments did not suppress height, and in some cases promoted it relative to the control, implied a complex mode of action that warranted further investigation into its effects on peanut plant architecture. Overall, the observed variation underscored the potential to fine-tune plant height a component of canopy structure through strategic PGR use.

Table 3. Mean values (±SEM) of leaf size, leaf width, number of leaves per plant, and plant height as influenced by different plant growth regulator applications

	Leaf Size (cm)	Leaf Width (cm)	Number of Leaves	Plant Height (cm)
Treatments				
GA_3BB10	3.45±0.12 cde	1.68±0.06 de	1075.00±20.56 a	36.56±1.86 bc
GA_3BB20	3.77±0.08 abcd	1.90±0.10 abc	752.33±16.09 de	40.66±1.67 a
GA_3FB10	4.13±0.17 a	1.92±0.05 abc	666.66±9.49 f	36.45±1.27 bc
GA_3FB20	3.84±0.07 abc	1.95±0.03 a	774.00±2.75 de	37.06±0.78 abc
SWBB40	3.30±0.10 e	1.58±0.07 e	672.83±7.56 f	36.76±1.13 bc
SWBBFB100	3.38±0.13 de	1.75±0.08 bcde	789.00±16.36 d	34.03±0.96 cd
SWFB60	3.50±0.07 bcde	1.73±0.04 cde	749.16±8.78 de	31.73±1.48 d
MCBB150	3.83±0.09 abc	1.83±0.04 abcd	858.50±20.51 c	36.66±1.07 bc
MCBB200	3.85±0.02 abc	1.94±0.06 a	713.00±16.34 ef	38.60±1.03 ab
MCFB150	3.93±0.33 ab	1.85±0.04 abcd	1057.83±32.69 a	37.16±1.06 abc
MCFB200	3.78±0.11 abcd	1.94±0.07 ab	869.33±25.29 c	38.36±0.89 ab
Control	3.88±0.14 abc	1.87±0.08 abc	988.11±25.38 b	32.80±0.47 d
Years				
2019	3.74±0.74	1.80±0.02	826.38±23.79	36.20±0.59
2020	3.70±0.06	1.86±0.03	834.57±24.27	36.61±0.61
Mean	3.72±0.05	1.83±0.02	830.48±16.88	36.40±0.42

SEM: Standard Error of the Mean. Letters show different groups in each column.

3.2. Effects of PGR on the number of branches, number of pods, pod weight, and 100-pod weight of peanut

The analysis of variance indicated a significant overall effect of PGR applications on the number of branches per plant ($p < 0.01$) (*Table 2*). However, the multiple comparison test did not reveal statistically significant differences among the treatment means for this trait (*Table 4*). Numerically, the number of branches ranged from 11.60 to 13.86, with the SWBBFB100 and GA_3BB10 treatments showing the highest and lowest mean values, respectively. This overall positive trend is supported by previous research. Faldu et al. (2018) reported that gibberellic acid applications increased the number of branches in groundnut, noting the importance of application dose. Similarly, Karthikeyan and Shanmugam (2015) found that seaweed extract applications enhanced branching in peanut, and Kim et al. (2011) observed an increase in branch number with mepiquat chloride application in flax. Although strict statistical separation was not achieved in the present study, the general tendency for PGR applications to produce numerically greater branch numbers than the lowest values aligns with the growth-promoting effects reported in the literature for these compounds.

Table 4. Mean values (±SEM) of the number of branches per plant, number of pods per plant, pod weight per plant, and 100-pod weight as influenced by different plant growth regulator applications

	Number of Branches	Number of Pods Per Plant	Pod Weight Per Plant (g)	100-Pod Weight (g)
Treatments				
GA_3BB10	11.60±3.42	25.97±1.38 d	51.76±0.38 d	279.80±1.30 d
GA_3BB20	12.63±0.62	28.37±1.19 c	55.26±0.52 c	290.00±0.78 b
GA_3FB10	13.16±0.92	33.34±1.73 a	59.24±0.33 b	297.44±1.23 a
GA_3FB20	12.56±0.79	22.89±1.54 f	70.70±0.53 a	287.90±0.48 c
SWBB40	13.20±0.70	19.71±1.46 hi	39.94±0.39 f	261.98±0.92 g
SWBBFB100	13.86±0.65	21.00±1.41 gh	37.68±0.73 g	249.77±1.21 i
SWFB60	13.03±1.00	19.15±1.27 i	35.01±2.04 h	239.43±0.85 j
MCBB150	12.30±0.51	21.92±1.18 fg	40.35±0.55 f	253.02±1.15 h
MCBB200	13.53±0.81	24.42±1.30 e	45.80±0.43 e	269.29±0.70 f
MCFB150	13.20±0.38	31.72±1.44 b	58.97±0.44 b	271.98±0.89 e
MCFB200	12.96±0.55	24.99±1.03 de	46.23±0.42 e	270.77±1.09 ef
Control	12.77±0.44	15.01±1.18 j	25.57±1.25 i	251.70±0.89 hi
Years				
2019	12.88±0.25	21.18±0.85 B	46.02±2.14 A	267.06±2.92 B
2020	12.91±0.27	26.90±0.89 A	48.39±1.93 B	270.12±2.93 A
Mean	12.90±0.18	24.04±0.70	47.21±1.44	268.59±2.06

SEM: Standard Error of the Mean. Letters show different groups in each column.

The combined analysis of variance indicated statistically significant differences among the treatments for the number of pods per plant ($p < 0.01$) (*Table 2*). The number of pods per plant varied considerably, ranging from 15.01 in the control to 33.34 in the GA_3FB10 treatment (*Table 4*). The applications that yielded the greatest number of pods were GA_3FB10 (33.34), MCFB150 (31.72), and GA_3BB20 (28.37). The literature substantiates the potential of PGRs to influence pod number. The positive effect of gibberellic acid (GA_3) observed in this study, where GA_3FB10 produced the highest pod count, aligns with findings in peanut (Patil, 2019), flax (Yagum et al., 2023), and soybean (Chen et al., 2023), though the response to dose can vary across species. Similarly, the increased pod number associated with the MCFB150 treatment is consistent with reports that mepiquat chloride can enhance this yield component in peanut (Gulluoglu, 2011; Arioglu et al., 2013), soybean (Abd et al., 2005), and flax (Kim et al., 2011). The effect of seaweed extract on pod number, as indicated by several studies in soybean and safflower (Behradfar et al., 2015; Kocira et al., 2019; Mannan et al., 2023), provides a context for understanding the performance of related treatments in this experiment. The findings of this experiment largely paralleled the existing literature, confirming that GA_3, mepiquat chloride, and seaweed extracts can be effective tools for increasing pod number in legumes. The standout performance of GA_3FB10 suggests that applying GA_3 at 10 ppm during the full bloom stage may be particularly conducive to pod set in peanut under the studied conditions. The fact that the control treatment yielded the lowest pod number underscores the general benefit of PGR application for this critical yield component.

According to the two-year average values, PGR applications were found to be statistically significant for both pod weight per plant and 100-pod weight ($p < 0.01$) (*Table 2*). Regarding pod weight per plant, a wide variation was observed, with values ranging from 25.57 g in the control to 70.70 g in the GA_3FB20 application (*Table 4*). The GA_3FB20 treatment yielded the greatest pod weight. For 100-pod weight, values varied between 239.43 g (SWFB60) and 297.44 g (GA_3FB10). A significant positive correlation was found between pod weight per plant and other yield components such as 100-pod weight, 100-seed weight, and shelling percentage (*Table 6*). The literature presented diverse findings. The substantial increase in pod weight with GA_3FB20 aligned with reports in flax (Yagum et al., 2023) but contrasted with a study in sunflower (Erdemli and Kaya, 2015). Similarly, the positive effects of seaweed extract (Kocira et al., 2019; Mannan et al., 2023) and mepiquat chloride (Abd et al., 2005; Gulluoglu, 2011; Arioglu et al., 2013) on pod weight reported in other crops provided a context for understanding the performance of various treatments in this experiment. The results of this experiment were largely consistent with the majority of the cited literature. The finding that GA_3FB20 resulted in the greatest pod weight per plant, while GA_3FB10 led to the highest 100-pod weight, highlighted the nuanced effect of gibberellic acid application timing and dose. Applying GA_3 at 20 ppm during full bloom appeared optimal for maximizing total pod weight per plant, whereas a 10 ppm application at the same stage may have favored the development of heavier individual pods. These outcomes, along with the observed positive correlations, demonstrated the potential of specific PGR regimens to enhance different facets of yield architecture in peanut.

3.3. Effects of PGR on 100-seed weight, shelling percentage, protein content, and pod yield of peanut

The combined analysis of variance indicated statistically significant differences among the treatments for 100-seed weight ($p < 0.01$) (*Table 2*). The 100-seed weight values ranged from 91.84 g in the control to 115.37 g in the GA_3FB10 application (*Table 5*). The GA_3FB10 treatment yielded the greatest 100-seed weight, which was significantly higher than most other treatments. A strong positive correlation was observed between 100-pod weight and 100-seed weight according to Pearson correlation analysis (*Table 6*). The literature widely supported the seed weight-enhancing potential of the tested PGRs. The superior performance of GA_3FB10 in this study aligned with numerous reports on the positive effect of gibberellic acid on 100-seed weight in peanut (Patil, 2019; El-Kamar et al., 2019), sunflower (Erdemli and Kaya, 2015), safflower (Heydari et al., 2021), and okra (Khrmashow et al., 2022). Similarly, most studies on seaweed extract reported increased seed weight in crops like soybean, sunflower, rapeseed, and safflower (Mannan et al., 2023; Habashy and Bishara, 2013; Matysiak et al., 2014; Behradfar et al., 2015), though a contrasting finding existed (Kocira et al., 2019). The beneficial effect of mepiquat chloride on this trait, consistent with the results for several MC treatments, was also documented in peanut (Gulluoglu, 2011; Arioglu et al., 2013; Yenikalayci and Arslan, 2023), soybean (Abd et al., 2005), flax (Kim et al., 2011), and cotton (Sawana et al., 2007). The findings of this experiment confirmed the established role of GA_3, seaweed extract, and mepiquat chloride in promoting seed filling and final seed mass. The fact that the maximum 100-seed weight was achieved with GA_3FB10 (10 ppm at full bloom), rather than with a higher GA_3 dose or a different compound, suggested a specific optimization point for this trait. This result, coupled with the strong correlation to 100-pod weight, indicated that management practices favoring overall pod filling concurrently enhanced individual seed development, which was crucial for yield quality.

The combined analysis of variance indicated statistically significant differences among the treatments for shelling percentage ($p < 0.01$) (*Table 2*). Regarding shelling percentage, the highest values were recorded in the GA_3FB20 (76.27%) and GA_3FB10 (74.84%) applications, whereas the lowest value was found in the control group (69.09%) (*Table 5*). The literature supported the positive effect of PGRs on shelling percentage observed in this study. El-Kamar et al. (2019) reported that gibberellic acid applications enhanced the shelling percentage in peanut. Similarly, Gulluoglu (2011), Arioglu et al. (2013), and Yenikalayci and Arslan (2023) demonstrated that mepiquat chloride applications increased the shelling percentage in peanut, emphasizing the importance of application dose and timing. The findings of this experiment were consistent with the cited literature. The superior shelling percentage achieved with GA_3FB20 and GA_3FB10 highlighted the efficacy of applying gibberellic acid during the full bloom stage for improving this key quality trait. This improvement suggested that these PGR applications may have positively influenced pod filling and seed development, resulting in a higher proportion of mature, well filled seeds a direct contributor to marketable yield and quality.

Table 5. Mean values (±SEM) of 100-seed weight, shelling percentage, protein content, and pod yield as influenced by different plant growth regulator applications

	100-Seed Weight (g)	Shelling Percentage (%)	Protein Content (%)	Pod Yield (kg da^{-1})
Treatments				
GA_3BB10	112.37±0.34 b	70.81±0.25 de	25.28±0.11 bc	493.02±3.63 d
GA_3BB20	112.78±0.28 b	73.70±0.21 c	25.43±0.08 b	526.05±4.93 c
GA_3FB10	115.37±0.24 a	74.84±0.23 b	24.48±0.11 de	563.55±3.13 b
GA_3FB20	112.06±0.77 b	76.27±0.20 a	25.31±0.14 bc	669.76±3.49 a
SWBB40	98.46±0.32 e	69.72±0.18 fg	25.23±0.13 bc	381.50±3.72 f
SWBBFB100	93.30±0.49 g	69.55±0.17 fg	24.32±0.26 e	360.34±7.07 g
SWFB60	94.93±0.41 f	69.42±0.14 g	25.21±0.06 bc	333.40±18.46 h
MCBB150	98.10±0.62 e	70.18±0.08 ef	24.85±0.07 cd	383.85±4.71 f
MCBB200	98.31±0.45 e	71.09±0.31 d	26.90±0.22 a	435.43±4.50 e
MCFB150	106.79±0.44 c	70.17±0.06 ef	24.47±0.17de	561.46±4.47 b
MCFB200	103.73±0.22 d	70.71±0.21 de	24.52±0.12 de	440.26±4.11 e
Control	91.84±0.29 h	69.09±0.30 g	23.16±0.16 f	248.93±12.72 i
Years				
2019	102.68±1.37	71.20±0.39	24.87±0.13	438.78±20.24 B
2020	103.66±137	71.39±0.38	24.99±0.17	460.81±18.08 A
Mean	103.17±0.96	71.30±0.27	24.93±0.10	449.79±13.54

SEM: Standard Error of the Mean. Letters show different groups in each column.

The combined analysis of variance indicated that the treatments had a statistically significant effect on protein content ($p < 0.01$) (*Table 2*). The protein content in the treatments varied between 23.16% in the control and 26.90% in the MCBB200 application (*Table 5*). The MCBB200 treatment yielded the greatest protein content. The literature indicates that PGRs can influence seed protein levels. Saini and Jain (2017) in peanut and Ghasil et al. (2023) in soybean reported that gibberellic acid applications increased protein content. Similarly, seaweed extract applications were shown to raise protein content in soybean, sunflower, and rapeseed (Kocira et al., 2019; Habashy and Bishara, 2013; Matysiak et al., 2014). The most pronounced increase in this study, however, was associated with mepiquat chloride (MCBB200), a finding consistent with reports in peanut (Gulluoglu, 2011; Arioglu et al., 2013), soybean (Abd et al., 2005), and cotton (Sawana et al., 2007), where this compound also enhanced protein content, with dose and timing being critical factors. The findings of this experiment aligned with the existing literature, confirming that PGR applications can be a tool for enhancing seed protein in peanut. The superior result from MCBB200 (mepiquat chloride at 200 ppm during beginning bloom) suggests that this specific regulator, applied at a relatively high dose during early reproductive growth, may be particularly effective in stimulating nitrogen metabolism or protein deposition in seeds. This is an important quality consideration, as higher protein content directly increases the nutritional value of the harvest.

The combined analysis of variance for the two years indicated statistically significant differences in pod yield among the treatments ($p < 0.01$) (*Table 2*). Regarding pod yield, the highest value was recorded in the GA_3FB20 application (669.76 kg da^{-1}), while the lowest value was obtained from the control (248.93 kg da^{-1}) (*Table 5*). A strong positive correlation was observed between pod yield and pod weight per plant according to Pearson correlation analysis (*Table 6*). The literature on the yield response to PGRs is extensive and generally supportive of the present findings. The superior pod yield with GA_3FB20 aligns with reports of gibberellic acid increasing yield in peanut (Saini and Jain, 2017; Patil, 2019), safflower (Heydari et al., 2021), okra (Khrmashow et al., 2022), soybean (Ghasil et al., 2023), and flax (Yagum et al., 2023), though a contrasting result was noted in sunflower (Erdemli and Kaya, 2015). Similarly, the yield-enhancing effect of seaweed extract documented in sunflower, peanut, soybean, rapeseed, and safflower (Habashy and Bishara, 2013; Osman and Salem, 2011; Karthikeyan and Shanmugam, 2015; Mannan et al., 2023; Matysiak et al., 2014; Behradfar et al., 2015) provides context for the performance of related treatments. The positive effect of mepiquat chloride observed in this study is also consistent with findings in peanut (Gulluoglu, 2011; Arioglu et al., 2013; Yenikalayci and Arslan, 2023), cotton (Sawana et al., 2007; Srikala et al., 2023), and flax (Kim et al., 2011). The pod yield findings of this experiment were congruent with the majority of literature reports. The result that GA_3FB20 produced the greatest pod yield represents a key agronomic finding. This treatment nearly tripled the yield of the control and significantly outperformed other PGR combinations, demonstrating its exceptional efficacy under the trial conditions. The strong correlation with pod weight per plant underscores that yield gains were primarily driven by increased pod mass rather than pod number alone. This study conclusively shows that the strategic application of specific PGRs, particularly GA_3 at the defined dose and timing, can dramatically enhance peanut productivity in the Eastern Mediterranean region.

Table 6. Correlation analysis for the investigated parameters according to average values of peanut for studied years

	LS	LW	LN	PH	NB	NP	PW	HPW	HSW	SP	PC
LW	**										
LN		-									
PH			-								
NB			-	-							
NP	*			**	-						
PW			-	**	-	**					
HPW	*	*	-	**	-	**	**				
HSW				**	-	**	**	**			
SP	*	**	-*	*	-	**	**	**	**		
PC	-	-	-*	*	-						
PY			-	**	-	**	**	**	**	**	

LS: Leaf size; LW: Leaf width; LN: Number of leaves; PH: Plant height; NB: Number of branches per plant; NP: Number of pods per plant; PW: Pod weight per plant; HPW: 100-pod weight, HSW: 100-seed weight; SP: Shelling percentage; PC; Protein content; PY: Pod yield. * and ** Correlation is significant at the 0.05 and 0.01 levels, respectively. "-": Negative correlation; > 0.900, > 0.800, > 0.700, > 0.500, < 0.500

3.4. Principal Component Analysis (PCA)

Principal component analysis (PCA) was performed to determine the effect of different PGRs and their application period and concentrations on peanut across agronomic and quality traits (*Figure 2*). The PCA revealed that the first three components (PCs), which had higher eigenvalue than 1.0, explained 80.369% of the total variance. PC1 accounted for 52.555% of the variance, highlighting its supreme role in the investigated parameters. On the other hand, PC2 and PC3 contributed to 14.581% and 13.233% of the variance, respectively. The biplot (*Figure 3*) illustrated the distribution of treatments and traits within the PC1-PC2 plane. The treatments involving GA_3, particularly GA_3FB10 and GA_3FB20, were positioned in close proximity to the vectors for key yield components such as pod yield, pod weight per plant, 100-pod weight, and shelling percentage. This spatial association indicated a strong positive relationship between these GA_3 applications and the primary yield-determining traits. Furthermore, PC1 was heavily loaded by pod yield, pod weight, 100-pod weight, 100-seed weight, shelling percentage, number of pods per plant, and plant height. PC2 was primarily associated with the number of leaves, number of branches, and protein content, while the remaining parameters were mainly loaded on PC3. The PCA results provide a synthesized view of the treatment effects. The clear clustering of high-yield traits along PC1, driven largely by GA_3-based treatments (GA_3FB10, GA_3FB20), visually confirms the central finding of this study: that gibberellic acid application during full bloom is the most influential factor for enhancing pod yield and its associated components. The separation of protein content onto PC2 suggests that this quality trait may be governed by a somewhat different set of physiological factors, potentially linked to treatments like MCBB200 which excelled in protein content but were not the top yield performers. This multivariate analysis reinforces the conclusion that while multiple PGRs can improve various traits, GA_3FB20 stands out as the most comprehensive treatment for optimizing overall yield architecture in peanut.

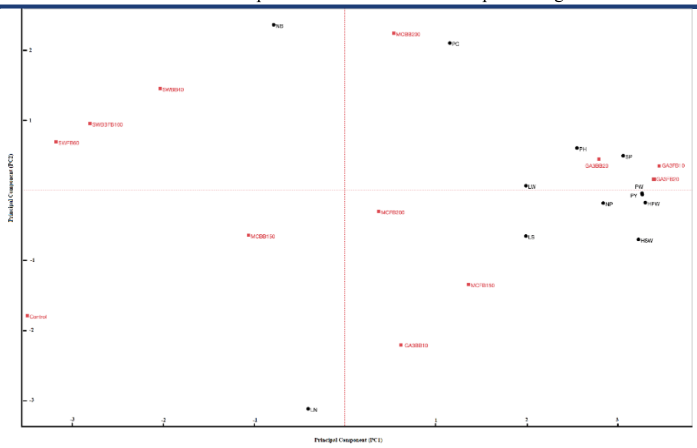

Figure 2. Relationships between investigated parameters and independent variables using PCA

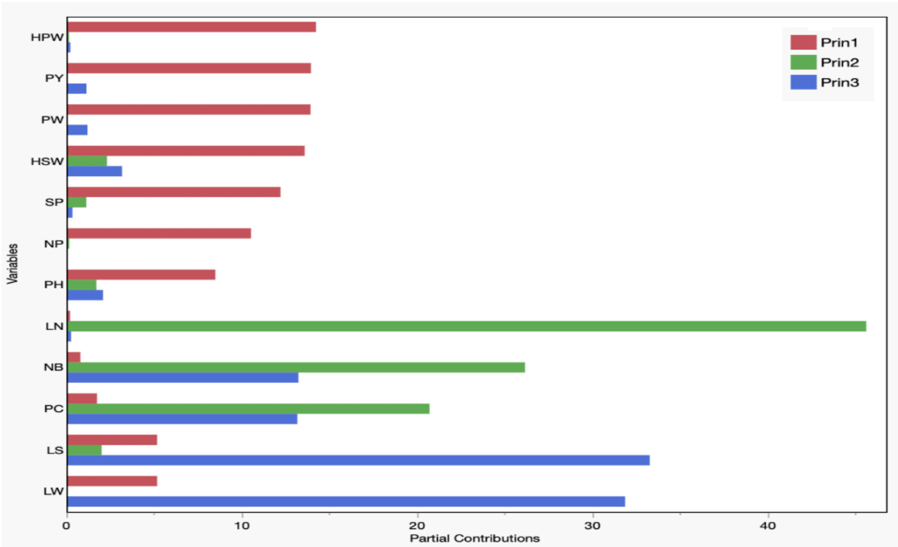

Figure 3. The plot of the partial contribution of variables

4. Conclusions

This study investigated the impact on peanut quality and yield of applying gibberellic acid, seaweed, and mepiquat chloride PGRs. The number of pods per plant, pod weight per plant, weight of 100 seeds, shelling percentage, protein content, and pod yield all increased significantly with the use of PGRs. Based on the trial findings, varying the dosage and timing of applying gibberellic acid and mepiquat chloride, two PGRs, to peanuts resulted in higher 100-seed weight, shelling percentage, and pod yield. As a result of the study, it was concluded that GA_3 applications in the full bloom stage with 10 to 20 ppm could be the optimum selection for achieving higher pod yield.

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Ethical Statement

There is no need to obtain permission from the ethics committee for this study.

Conflicts of Interest

There is no conflict of interest between the article authors.

Authorship Contribution Statement

Concept: Yilmaz, M., Sahin, C. B.; Design: Yilmaz, M., Sahin, C. B.; Data Collection or Processing: Yilmaz, M.; Statistical Analyses: Sahin, C. B.; Literature Search: Yilmaz, M., Sahin, C. B.; Writing, Review and Editing: Yilmaz, M., Sahin, C. B.

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