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RESEARCH ARTICLE OPEN ACCESS

Plant density influences yield, yield components, lint quality and seed oil content of cotton genotypes

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Abstract – Choosing suitable varieties and manipulating plant population are crucial management aspects in any cropping system that goals to improve yield, quality and the balance between plant demand and environmental resource availability. A two-year field experiment was conducted at Tehran, Iran, in a split plot design and replicated thrice to examine the effect of the planting density (low, moderate and high) on ten cotton genotypes. In term of lint yield and among the cotton genotypes G8 (1269 $kg \cdot ha^{-1}$), G4 (1263 $kg \cdot ha^{-1}$), G1 (1239 $kg \cdot ha^{-1}$) and G2 (1123 $kg \cdot ha^{-1}$) were statistically at par with each other but significantly superior to G7 (914 $kg \cdot ha^{-1}$) and G9 (936 $kg \cdot ha^{-1}$). Lint yield in high plant density (1386 $kg \cdot ha^{-1}$) was found to be remarkably superior over medium and low plant density (1029 and 890 $kg \cdot ha^{-1}$, respectively) by average of 25.7% and 35.7%, respectively. Cotton genotypes at low plant density had higher boll $plant^{-1}$ (6.46% and 15.3%, respectively), lint percentage (5.8% and 12%, respectively) and lint strength (0.6% and 1.9%, respectively) compared to moderate and high plant densities. The genotypes cultivated at high plant density produced higher seed and lint yield, higher lint elasticity and lower seed oil content, lint length and lint quality index. Based on this experiment, it is concluded that high seed cotton yield can be achieved at high plant density while higher lint quality can be yielded at low plant density.

Keywords: light interception / lint properties / oil content / plant morphology / plant structure

Résumé – La densité des plantes influence le rendement, les composantes du rendement, la qualité de la fibre et la teneur en huile des graines des génotypes de coton. Le choix de variétés adaptées et l'optimisation du peuplement végétal constituent des décisions centrales dans tout système de culture qui vise à améliorer le rendement, la qualité et l'équilibre entre les besoins des plantes et la disponibilité des ressources dans l'environnement. Une expérimentation au champ a été conduite pendant deux ans à Téhéran, Iran, selon un dispositif expérimental de type Split-Plot à trois répétitions, pour examiner l'effet de la densité de plantation (faible, modérée et élevée) sur dix génotypes de coton. En termes de rendement en fibres, les génotypes de coton G8 (1269 $kg \cdot ha^{-1}$), G4 (1263 $kg \cdot ha^{-1}$), G1 (1239 $kg \cdot ha^{-1}$) et G2 (1123 $kg \cdot ha^{-1}$) n'étaient pas statistiquement différents mais significativement supérieurs à G7 (914 $kg \cdot ha^{-1}$) et G9 (936 $kg \cdot ha^{-1}$). Le rendement en fibres à la densité de plantation élevée (1386 $kg \cdot ha^{-1}$) s'est avéré bien supérieur à celui des densités de plantation moyenne et faible (1029 et 890 $kg \cdot ha^{-1}$, soit +25,7 % et +35,7 % respectivement). Comparativement aux génotypes cultivés à des densités de plantation moyenne et élevée, les génotypes de coton conduits à faible densité ont produit plus de capsules par plante (+6,5 % et +15,3 %, respectivement) et ont permis d'atteindre un pourcentage de fibres plus élevé (+5,8 % et +12 %, respectivement) ainsi qu'une meilleure résistance de la fibre (0,6 % et 1,9 %, respectivement). Les génotypes cultivés à une densité de plantation élevée ont permis d'atteindre un rendement en graines et en fibres plus élevé et une plus forte élasticité des fibres ; par contre, ils ont montré une teneur en huile des graines, une longueur de fibres et un indice de qualité des fibres plus faibles. Sur la base de cette expérimentation, on peut conclure qu'un rendement élevé en coton graine peut être obtenu avec une densité de plantation élevée, tandis qu'une qualité de fibre supérieure peut être obtenue avec une faible densité de plantation.

Mots clés : interception légère / propriétés pelucheuses / teneur en huile / morphologie végétale / structure végétale

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Highlights

- Lower carbohydrate availability dense plants result lower bolls plant^{-1}.
- Reduction of growth period to crop maturity, in dense plant result fewer bolls plant^{-1}.
- High plant density lessened the sunlight penetration to canopy, which causes boll abscission.
- Seed oil content has a negative association with lint percentage.
- Increase in plant density reduced the boll weight plant^{-1} due to lower lint and seed mass.

1 Introduction

The cotton (*Gossypium hirsutum* L.) is the only fibrous crop primarily cultivated for fiber production in the world. However, cotton cultivation is currently facing rising production costs, leading producers to explore new and high yield potential cultivars. Crop management practices are another way to improve fiber quality and quantity while maintaining lint yield. It is worth pointing out that lint yield is negatively related to fiber quality and accessing methods to increase fiber quality while preserving cotton yield have become the focus of studies (Luo *et al.*, 2019; Keshavarz, 2020).

Cotton growth and development is highly affected by genetic and environmental factors. One of these factors affecting cotton quality and yield is optimum plant density, and the determination of a suitable plant population differs by environment, cultural practices and cultivar (Dai *et al.*, 2015; Keshavarz *et al.*, 2021a). Usually, producers and farmers choose plant density based on tradition rather than variety requirement, potentially resulting in yield losses.

Plant population directly affects moisture availability, light interception and wind movement, which in turn influences the branching design, plant height, canopy architecture, boll shedding, plant maturity and balance between vegetative and reproductive growth (Romano *et al.*, 2011). Establishing an appropriate plant density optimized the resource use, promote the water and fertilizer use efficiency and finally increase crop productivity and higher radiation interception due to early canopy closure. High plant density can prolong the vegetative phase, delay plant maturity and decrease net photosynthesis due to lower chlorophyll content and RUBP carboxylase enzymes activity (Li *et al.*, 2019; Keshavarz *et al.*, 2021a, b, c). Dense planting can promote auxin content and polar transport by enhancing the expression of the auxin polar transport gene (GhP1N1) and auxin biosynthesis gene (GhYUC5) (Khan *et al.*, 2019). It can also prevent branching and limit plant structure by enhanced strigolactone content due to gene expression in the tips of vegetative branches followed by reducing gibberellic acid, indole acetic acid, cytokinin and brassinosteroid contents (Jiang *et al.*, 2012; Keshavarz *et al.*, 2018).

However, the relationship between lint yield and yield components of cotton are complicated. Darawsheh *et al.* (2022) documented that lint yield was mostly affected by bolls plant^{-1}, followed by seeds boll^{-1} and lint mass seed^{-1}. Zhi *et al.* (2016) revealed high plant density decreased seed surface area, the number of fibers per unit and lint mass. Therefore, selection of smaller bolls with higher number of seeds might be useful because of the higher surface area for lint production (Keshavarz *et al.*, 2016; Ul-Allah *et al.*, 2021). Gao *et al.* (2012a, b) noted that seed size influenced lint production because cotton fiber is an extension of the seed's epidermal cell. Khan *et al.* (2017a) discovered that boll weight, number of bolls plant^{-1} as well as seed weight were significantly affected by plant density. On the other hand, low plant density prevents the expression of all-genetic potential, changes lint characteristics and reduces lint strength (Romano *et al.*, 2011) while increasing lint micronaire (Suminarti *et al.*, 2016). It is known that lint quality and maturity have an important role on yarn characteristics and spinning properties. Yang *et al.* (2014) resulted that a rational plant density provided a better canopy microenvironment to achieve higher lint percentage. In addition, the yield traits are a function of the cultivar (Hosseini *et al.*, 2023). Lint fineness is acknowledged as ratio of lint cell-wall thickening to diameter of the lint and it depends on deposition of cellulose in lint cell, which is sensitive to growth conditions (Gao *et al.*, 2012a, b). Synthesis of cellulose needs many enzymes and organic molecules that among them sucrose synthase and sucrose phosphate synthase are two essential enzymes in the carbon partitioning and sucrose synthesis (Khan *et al.*, 2017b). Sucrose synthase provides initial carbon supply and converts to other macromolecular substances, such as cellulose for fiber synthesis and lipid in embryos. In the sucrose synthesis cycle, sucrose is catalyzed by sucrose synthase to provide fructose, while UDP-glucose provides substrates for the biosynthesis of cellulose (Yadav *et al.*, 2013). The fructose released by sucrose synthase is reprocessed into another sucrose cycle to reproduction further cellulose accumulation, a pathway that regulates cellulose production under stress conditions (Liu *et al.*, 2013). All these processes and enzymes are influenced by environmental conditions, but their response varies in different plants and/or how they are cultivated.

Producers of fiber continuously seeking for proper plant density new cotton genotypes aiming for higher lint yields. In presented study, we focused on cotton yield and lint quantities among ten cotton cultivars and hybrids and how these may influence by plant density. Therefore, the objective of this experiment was to determine the optimum plant density for hybrids and cultivars of cotton and what is the effect of high and low plant density on yield components and quality traits.

2 Materials and method

2.1 Study site and soil

A two years field study was carried out at Varamin Cotton and Fiber Crop Research Department, Tehran, Iran from 2017 to 2018. Varamin is located in the western zone of Tehran located at latitude 35.21°E and longitude: 51.38°N with an altitude of 927 m above mean sea level. Figure 1 is provided the total monthly precipitation and monthly averaged temperatures during the cotton-growing season. The soil in experimental site had loamy-sandy texture, neutral pH, 0.6% organic matter, low total nitrogen content, 15.9 mg · kg^{-1}

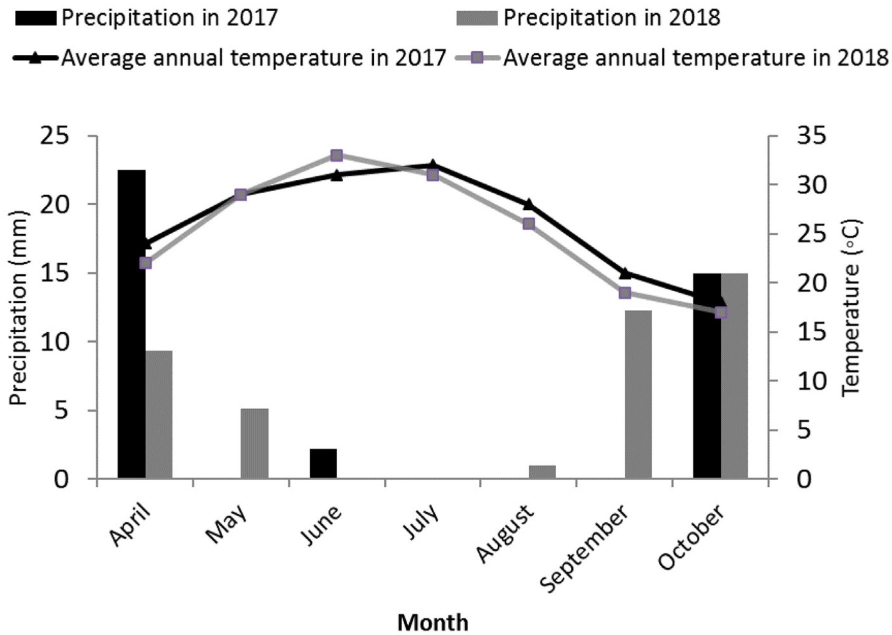

Fig. 1. Average monthly air temperature and precipitation during the period of April–October in 2017 and 2018.

available P (Olsen) and 510 $mg \cdot kg^{-1}$ available K in the top 30 cm of the soil profile.

Before sowing, the experimental field was ploughed and disking with a reel and harrow conditioner to smoothing seedbeds. The experimental design was a split plot with 30 treatment combinations in four replications. The main plot consists of three-intra row spacing of 20 cm (T1), 30 cm (T2) and 40 cm (T3) (with plant densities viz. 6.25, 4.16 and 3.125 plants $\cdot m^{-2}$, respectively) with fixed row spacing of 80 cm. Each subplot size was 3.3 m wide and 6 m in length with four rows. Subplot comprised of ten *G. hirsutum* genotypes including six cultivars of Varamin, Bakhtegan, Sajedi, Sahel, T2 and T14 and four hybrids Sahel × Sajedi, Bakhtegan × T2, Varamin × T14 and Sajedi × T14 (referred hereafter as G1, G2, G3, G4, G5, G6, G7, G8, G9 and G10, respectively). All seeds got from the Varamin Cotton and Fiber Crop Research Department, Tehran. Before sowing, a heavy pre-sowing irrigation was applied, after which the cotton genotypes were seeded on April 20th by using the manual hill-drop planting method. Thinning was done (at the third leaf stage) to achieve uniform stands of the desired plant densities. All the potassium (in the form of potassium sulfate, 41.5% K) and half of the nitrogen (in the form of urea, CH_4N_2O, 46% N) were applied before planting. The other half of the nitrogen was top-dressed at flowering stage. All insect-pests and weeds were controlled and other cultural practices were in coordination with Varamin Cotton and Fiber Crop Research Department (Keshavarz *et al.*, 2021a; Hassanzadehdelouei *et al.*, 2022).

2.2 Plant data collection and analysis

Data were collected for number of boll plant^{-1}, boll weight, fiber yield, seed cotton yield ($kg \cdot ha^{-1}$), lint and cotton seed oil content (%) at maturity stage (when approximately 60% of the bolls were open) for each fruiting position. In each year, observations were taken from 10 randomly-guarded plants from the two central rows of each plot (except plants in the first and last 50 cm of each row) and the average was calculated for the number of boll plant^{-1} and boll weight. Seed cotton (including seed and lint) was manually collected from 2 m^{-2} and air dried for three days under the sun until the water content reached 12%). Seed and lint were separated using a roller-ginning machine (made in Anyang, China). Seed cotton yield ($kg \cdot ha^{-1}$), lint yield ($kg \cdot ha^{-1}$) and lint percentage (as lint, divided by total seed cotton yield) was calculated after ginning. The seed oil content was measured by using the Soxhlet extraction apparatus (Sadasivam and Manickam, 1995).

The lint properties were measured on the lint picked from the 10 boll samples of each plot and then combined. The lint from each plot were sent to laboratory with high volume instrument lint analysis (HVI model HVI Classic 900) for lint quality measurement such as lint length (as 2.5% of the span length and expressed as mm), lint uniformity (as the ratio of the mean length to the upper-half mean length and expressed as a percentage), lint strength (as the force $cN \cdot tex^{-1}$ necessary to break the fiber bundle), lint fineness (as the fineness and maturity of the lint, expressed in standard and expressed as $\mu g \cdot in^{-1}$), lint elasticity, and fiber quality index (Papastylianou and Argyrokastritis, 2014).

2.3 Statistical analysis

The variance of two years of data was analyzed using ANOVA and when the Ftest indicated statistical significance, the LSD's mean wise comparison test (honest significant difference, at $P < 0.01$ or $P < 0.05$) was used to verify the significance of differences among treatment means of main effect and the significant interaction effects were separated by slicing method. SAS 9.1 and S-PLUS ver. 6.1 software, USA were used for Principal Component Analysis (PCA) based on biplot and clustering analysis.

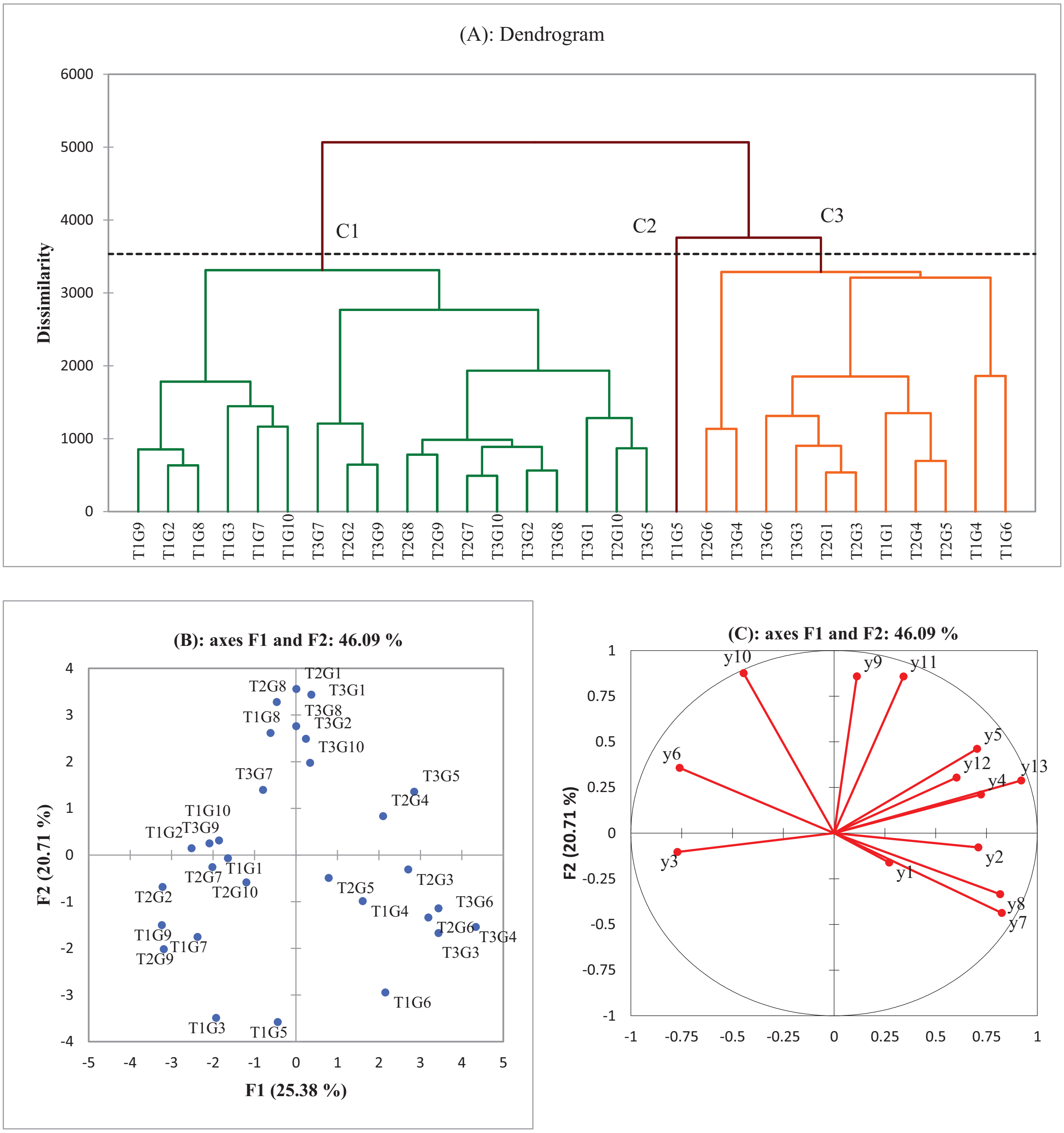

Fig. 2. The results of dendrogram based on cluster analysis (A) and biplot of first and second components based on principal component analysis (B and C). T1: 6.26 plant · m^{-2}; T2: 4.16 plant · m^{-2}; T3: 3.125 plant · m^{-2}; G1: Varamin; G2: Bakhtegan; G3: Sajedi; G4: Sahel; G5: T2; G6: T14; G7: Sahel × Sajedi; G8: Bakhtegan × T2; G9: Varamin × T14; G10: Sajedi × T14. Y1: bolls number $plant^{-1}$; Y2: boll weight; Y3: lint yield; Y4: seed cotton yield; Y5: lint percentage; Y6: lint length; Y7: lint uniformity; Y8: lint fineness; Y9: lint strength; Y10: lint elasticity; Y11: lint quality indices; Y12: oil seed content; Y13: cotton seed.

3 Results

3.1 Cluster and PCA analysis

Cluster analysis divided the all-30 treatments into three groups, composed of eighteen, one and eleven treatments respectively (Fig. 2A). Based on the bi-plot results (Figs. 2B and 2C), T1G8, T2G1, T2G8, T3G1, T3G2, T3G8, T3G10 and T3G7 formed one group, which was strongly associated with lint strength, lint elasticity and lint quality indices. Treatments T1G1, T1G2, T1G7, T1G9, T1G10, T2G2, T2G7, T2G9, T2G10 and T3G9 were classified in another group, which was related to lint yield and lint length. Treatments T1G4, T1G6, T2G3, T2G5, T2G6, T3G3, T3G4 and T3G6 formed an adjacent group, and were related with number of bolls $plant^{-1}$, boll weight, lint uniformity and lint fineness.

Table 1. Combined analysis of variance on some agronomic traits, lint quality and quantity of cotton (*Gossypium hirsutum* L.) as affected by plant density and genotype treatments.

Source of variation	df	BN	BW	LY	SCY	LP	LL
Year	1	1691**	198**	1 080 256*	25 018 485**	4858**	103**
Block (Year)	6	18.8	0.43	86 693	382 808	42.6	3.1
Plant density (D)	2	247**	0.51ns	5 237 738**	105 369 279**	279*	10.7**
Year × D	2	104**	1.33*	59 068ns	1 234 379*	13ns	3.6ns
D × Block (Year)	12	11	0.25	118 995	303 416	43	1.37
Genotype (G)	9	165**	8.65**	379 848**	1 432 316**	372**	118.7**
D × G	18	30*	0.83**	113 368ns	324 600ns	42ns	1.9ns
Year × G	9	67**	3.6**	145 046ns	1 505 357**	314**	16**
D × G × Year	18	38**	0.85**	154 481ns	248 386ns	84*	3.3ns
Error	162	15.7	0.34	110 153	289 887	42.7	2.32
CV (%)		18.6	14.02	30.1	13.8	22.3	4.7

Source of variation	df	LU	LF	LS	LE	LQI	OS
Year	1	70*	0.27ns	73*	1.02*	1 808 504ns	0.22ns
Block (Year)	6	10	0.39	5.4	0.15	20 008 382	1.014
Plant density (D)	2	2.05ns	0.51*	8.54*	0.68**	7 561 724ns	57**
Year × D	2	0.2ns	0.1ns	9.5*	0.00007ns	11 609 172ns	0.0001ns
D × Block (Year)	12	2.07	0.098	1.7	0.05	9 898 409	2.07
Genotype (G)	9	4.46ns	1.58**	222**	5.64**	262 399 906**	4.53ns
D × G	18	1.79ns	0.17ns	6.07*	0.31**	11 862 971**	6.3ns
Year × G	9	1.92ns	0.23ns	17**	0.00058ns	33 646 849**	0.00003ns
D × G × Year	18	1.16ns	0.087ns	8.04**	0.00003ns	8 154 551ns	0.00002ns
Error	162	2.97	0.12	3.12	0.09	4 891 902	5.5
CV (%)		2.03	8.3	5.4	4.7	10.6	15.09

BN: boll number plant^{-1}; BW: boll weight; LY: lint yield; SCY: seed cotton yield; LP: lint percentage; LL: lint length; LU: lint uniformity; LF: lint fineness; LS: lint strength; LE: lint elasticity; LQI: lint quality indices; OS: seed oil content. ns, **, * indicate as no significance and significance at P levels of 0.01 and 0.05, respectively.

3.2 Number of bolls plant^{-1}

The results showed that the main effect of year, plant densities, cotton genotypes and their interaction had significant effect on bolls plant^{-1} (Tab. 1). For both years, remarkable differences in boll plant^{-1} averaged across the cotton genotypes were found among the plant densities. In the first year, the bolls plant^{-1} was the highest under moderate to low plant density (4.16 and 3.12 plant · m^{-2}) for G3 (24.3) and G4 (25.5), respectively while under high plant density conditions, G6 (23.1) had the higher boll plant^{-1} (Tab. 2). However, in high plant density and low plant density, there was no significant difference ($P < 0.05$) between G3, G4, G5, G6 and G9 genotypes. The maximum bolls plant^{-1} in the first year (averaged by plant density treatments), was obtained by G3 (24 boll plant^{-1}). Quite different results were obtained in the second year, in which high, moderate and low plant densities produced the highest number of bolls plant^{-1} for G4 (31.1), G7 (30.9) and G6 (29.8), respectively. However, in moderate and low plant density, almost all genotype was statistically at the same level (Tab. 2). It should be noted that the maximum boll plant^{-1} in second year (averaged by plant density) was found in G3 (26.7 boll plant^{-1}) and G4 (27.2 boll plant^{-1}). Averaging all genotype treatments, boll plant^{-1} in low plant density was 12.5% and 13.7% (in first year), and 17.5% and 0.6% (in second year) higher than high and moderate plant density, respectively (Tab. 2). Averaging across years and genotypes, the boll plant^{-1} was 19.3 per plant at high plant density and increased by 9.8% and 15.7% at moderate and low plant density.

3.3 Boll weight

Boll weight was significantly ($P < 0.05$) affected throughout the two years by different genotypes and plant densities (Tab. 1). At high plant density and in first year, G1 and G10 recorded significantly higher boll weight than other genotypes (Tab. 2). Different results were observed at moderate and low plant density. Cotton genotypes G1 (6.6 g), G8 (5.7 g) and G10 (6.0 g) at moderate plant density and cotton genotype G1 (6.3 g), G7 (5.7 g), G8 (6.1 g) and G10 (6.4 g) at low plant density significantly had higher boll weight than other genotypes (Tab. 2). In term of boll weight affected by plant density × cotton genotype in second year, high, moderate and low plant density produced the maximum boll weight for G1 (4.3 g), G1 (4.06 g) and G2 (4.5 g), respectively (Tab. 2). In the first year, the boll weight at low plant density (averaged by cotton genotypes) was 5.4% and 2.5% higher than high and

Table 2. Mean comparison of the three-way interaction of year × plant density × genotype on boll number, boll weight, lint percentage and lint strength of cotton (*Gossypium hirsutum* L.) in 2017 and 2018 growing periods.

		BN (plant^{-1})		BW (g)		LP (%)		LS (g·tex^{-1})	
		2017	2018	2017	2018	2017	2018	2017	2018
6.26 plan·m^{-2}	G1	13.7c	16.9de	6.04a	4.3a	25.2a	34.0a-d	30.6cd	30.4c
	G2	15.0bc	15.5e	5.4a-d	4.2a	24.7a	25.8de	30.8cd	29.2c
	G3	22.8a	24.3b	4.2e-g	2.5cd	16.8b	28.1c-e	29.6de	36.2a
	G4	19.1ab	31.1a	5.0b-d	2.1d	24.6a	36.6a-c	36.3b	35.6ab
	G5	20.9a	17.8c-e	4.8c-e	4.1ab	19.5ab	30.0b-d	32.3c	33.5b
	G6	23.1a	16.8de	3.6g	3.6b	25.3a	40.8a	39.5a	34.4ab
	G7	15.3bc	17.8c-e	4.6d-f	4.1ab	24.2ab	19.1e	30.2cd	28.4c
	G8	15.0bc	21.2b-d	5.6a-c	3.1c	26.4a	35.6a-d	31.6cd	30.3c
	G9	19.8ab	25.6ab	3.9fg	2.7c	21.3ab	26.4c-d	27.7e	28.1c
	G10	13.5c	22.7bc	5.8ab	3.0c	21.8ab	39.3ab	31.6cd	30.5c
4.16 plant·m^{-2}	G1	13.5e	22.1bc	6.6a	4.06a	35.2a	30.9c-f	32.2c	29.6c
	G2	16c-e	23.5a-c	4.9e-i	2.9cd	20.4g-i	33.2c-e	29.4de	28.9c
	G3	24.3a	28.3a-c	4.0i-k	2.6cd	30.3a-f	22.07f	38.0b	36.0ab
	G4	19.6b	26.5a-c	5.3c-g	2.7cd	27.5a-g	36.6a-c	36.0b	37.9a
	G5	18.9b-d	22.9a-c	5.3c-g	3.02b-d	18.8hi	34.5b-d	32.1c	31.1c
	G6	19.4bc	23.9a-c	3.6k	2.6cd	20.6g-i	37.2a-c	40.9a	33.8b
	G7	14.2e	30.9a	5.1d-h	2.4d	25.0b-i	24.5ef	31.6cd	28.7c
	G8	15.3de	24.1a-c	5.7a-e	3.4a-c	32.5a-c	45.9a	31.8cd	29.3c
	G9	19.8b	20.9c	3.9jk	3.9ab	19.4g-i	26.6d-f	28.0e	29.7c
	G10	14.7e	29.6ab	6.0a-c	3.1a-d	20.1g-i	43.0ab	31.4cd	28.9c
3.125 plant·m^{-2}	G1	15.6cd	18.2c	6.3ab	3.7b	32.1a-d	42.2ab	30.7bc	31.3b
	G2	20.9ab	22.3bc	5.3c-g	4.5a	33.1a	31.0b-e	31.7bc	29.7bc
	G3	24.9a	27.7ab	4.3h-k	2.6e	20.5g-i	30.6c-e	36.9a	35.8a
	G4	25.5a	24.2ab	4.6g-j	2.9c-e	24.1d-i	41.0a-c	38.2a	36.3a
	G5	24a	29.4a	5.0d-h	2.6de	31.0a-e	29.2de	32.5b	31.4b
	G6	23.9a	29.8a	3.7jk	2.6de	23.9d-i	44.7a	37.6a	35.0a
	G7	16.7b-d	28.9a	5.7a-e	3.3b-d	25.7b-h	21.1e	30.1bc	30.2b
	G8	15.1d	27.5ab	6.1a-c	2.8c-e	23.8d-i	40.5a-d	32.6b	29.7bc
	G9	20.7a-c	24.5ab	4.3h-k	3.5bc	23.6e-i	34.1a-d	28.5c	27.9c
	G10	16.4b-d	21.9bc	6.4a	3.7b	22.6f-i	45.4a	31.9b	31.3b

BN: boll number plant^{-1}; BW: boll weight; LP: lint percentage; LS: lint strength. G1: Varamin; G2: Bakhtegan; G3: Sajedi; G4: Sahel; G5: T2; G6: T14; G7: Sahel × Sajedi; G8: Bakhtegan × T2; G9: Varamin × T14; G10: Sajedi × T14. By slicing method, each studied trait in each year is separated by blank rows. Means within each column of each section followed by the same letter are not significantly different ($P < 0.05$).

moderate plant density, respectively (Tab. 2). In second year, the boll weight at low plant density (averaged by cotton genotypes) was 4.4% lower and 4.9% higher than high and moderated plant density, respectively (Tab. 2). When averaged across the cotton genotypes and two years, the boll weight at high plant density (4.13 g) was slightly higher than moderate plant density (4.05 g) and low plant density (4.19 g), with an average of 1.9% and 1.4%, respectively (Tab. 2).

3.4 Lint yield

Lint yield was significantly ($P < 0.05$) affected by different year, plant densities and genotypes (Tab. 1). A significant difference in lint yield existed between year and lint yield in 2018 (1169 kg·ha^{-1}) was significantly higher than that in 2017 (1035 kg·ha^{-1}) because of higher air temperature in last two month growing season (Fig. 1). Cotton sowing with dense planting (6.26 plant·m^{-2}) had the highest lint yield (1386 kg·ha^{-1}) while cotton sowing with moderate and low plant population resulted in lower lint yield with average of 25.7% and 35.7% rather than high plant density, respectively (Tab. 3). Cotton genotype G8 (1269 kg·ha^{-1}), had significantly higher lint yield than other genotypes and followed by G4 (1263 kg·ha^{-1}), G1 (1239 kg·ha^{-1}), G2 (1223 kg·ha^{-1}) and G6 (1093 kg·ha^{-1}) (Tab. 3). Correlation was achieved positive and significant for the lint yield with seed cotton yield and lint percentage (Tab. 3).

Table 3. Mean comparison of simple effect of year, plant density and genotype on some measured traits of cotton (*Gossypium hirsutum* L.).

Main effect	LY ($kg \cdot ha^{-1}$)	LU (%)	LE (%)	
Year				
2017	1035b	85.1a	6.5b	
2018	1169a	84.0b	6.6a	
Plant density	LY ($kg \cdot ha^{-1}$)	LL (mm)	LF ($\mu g \cdot in^{-1}$)	OS (%)
6.26 $plant \cdot m^{-2}$	1386a	31.5b	4.22ab	14.8b
4.16 $plant \cdot m^{-2}$	1029b	31.9ab	4.13b	16.4a
3.125 $plant \cdot m^{-2}$	890c	32.2a	4.29a	15.2b
Genotype	LY ($kg \cdot ha^{-1}$)	LF ($\mu g \cdot in^{-1}$)		
G1	1239ab	3.95ef		
G2	1123abc	4.36bc		
G3	1028cd	3.87f		
G4	1263ab	4.04ef		
G5	1078bcd	4.32c		
G6	1093abcd	4.66a		
G7	914d	4.24cd		
G8	1269a	4.54ab		
G9	936cd	4.08de		
G10	1079bcd	4.08de		

LY: lint yield; LL: lint length; LU: lint uniformity; LF: lint fineness; LE: lint elasticity; OS: seed oil content. G1: Varamin; G2: Bakhtegan; G3: Sajedi; G4: Sahel; G5: T2; G6: T14; G7: Sahel × Sajedi; G8: Bakhtegan × T2; G9: Varamin × T14; G10: Sajedi × T14. Means within each column of each section followed by the same letter are not significantly different ($P < 0.05$).

3.5 Seed cotton yield

The analysis of variance results (Tab. 1) showed that effects of year, planting density, cotton genotypes, and interaction of year × genotypes were significant on seed cotton yield (Tab. 1). In 2017, maximum seed cotton yield was obtained in G4 (4736 $kg \cdot ha^{-1}$) and G5 (4726 $kg \cdot ha^{-1}$) followed by G3 (4524 $kg \cdot ha^{-1}$) (Tab. 4). However, different results were obtained in 2018, in which cotton genotypes G2 (4053 $kg \cdot ha^{-1}$), G3 (3960 $kg \cdot ha^{-1}$), G7 (3965 $kg \cdot ha^{-1}$) and G1 (3692 $kg \cdot ha^{-1}$) produced significantly the highest seed cotton yield (Tab. 4). Averaged by cotton genotypes, seed cotton yield was about 15% higher in 2017 (4205 $kg \cdot ha^{-1}$) than in 2018 (3560 $kg \cdot ha^{-1}$). Averaged over years, seed cotton yield of G3 (4242 $kg \cdot ha^{-1}$) was higher than other genotypes, which followed G2 (4038 $kg \cdot ha^{-1}$), G4 (4081 $kg \cdot ha^{-1}$) and G5 (4097 $kg \cdot ha^{-1}$) (Tab. 4). When compared with high plant density, the moderate and low plant densities caused decreased 32.9% and 42.2% in 2017, 28.9% and 44.1% in 2018 in seed cotton yield, respectively (Fig. 3). When averaged across the plant densities, the seed cotton yield at second year (3560 $kg \cdot ha^{-1}$) was less than first year (4206 $kg \cdot ha^{-1}$) by average of 15.3% (Fig. 3). The seed cotton yield at low plant densities (averaged over the two years), was less than moderate and high plant densities by averaged of 17.3% and 43% (Fig. 3). Dai *et al.* (2015), Luo *et al.* (2019) and Romano *et al.* (2011) derived information on seed $boll^{-1}$ and significant relation between seed $boll^{-1}$ with seed cotton yield, and other yield characters in *G. hirsutum* and stated that seed $boll^{-1}$ is an important yield factor and manage boll weight, lint percentage, seed cotton yield, lint yield and seed oil content.

3.6 Lint percentage

Lint percentage was significantly ($P < 0.05$) influenced by year, planting density, cotton genotypes and interaction of year × cotton genotypes and year × plant density × cotton genotypes (Tab. 1). In the case of mean comparison (Tab. 2), some differences were clear between two experimental years. In 2017, the highest lint percentage of high, moderate and low plant density was obtained in cotton genotypes of G8 (26.4%), G1 (35.2%) and G2 (33.1%), respectively. However, diverging results were obtained in the second year, when the highest lint percentage of high, moderate and low plant density was obtained in cotton genotypes of G6 (40.8%), G8 (45.9%) and G10 (45.4%), respectively. Averaged over 2017 and 2018, regardless of planting date, G8 (34.1%) and G7 (23.2%) had the highest and lowest lint percentage (Tab. 2). On average across genotypes, lint percentage under high plant density conditions was 8% and 11.7% in 2017, 5.6% and 12.2% in 2018 lower than under moderate and low density, respectively (Tab. 2). Averaged across plant density treatments, G1 (30.8%) and G10 (42.5%) had the highest lint percentage of the first and second year, respectively. The highest lint percentage of high, moderate and low plant density (on average across years) was found in cotton genotypes G6 (33.05%), G8 (39.2%) and G1 (37.15%), respectively.

3.7 Lint length

Significant variation between year, planting densities, cotton genotypes, and interaction of year × genotypes was found for lint length (Tab. 1). Under high density (6.26 $plant \cdot m^{-2}$),

Table 4. Mean comparison of the two-way interaction of year × genotype on seed cotton yield, lint length and lint quality indices of cotton (*Gossypium hirsutum* L.) in 2017 and 2018 growing periods.

Genotype	SCY ($kg \cdot ha^{-1}$)		LL (mm)		LQI	
	2017	2018	2017	2018	2017	2018
G1	4049c	3692abc	31.5cd	31.2cd	21 430b	20 299cd
G2	4023c	4053a	28.8fg	30.1de	17 751d	16 842f
G3	4524ab	3960ab	32.9ab	37.5a	21 746b	25 861b
G4	4736a	3427cde	33.4ab	36.9a	25 124a	29 210a
G5	4726a	3468cd	32.1bc	32.8b	21 420b	19 888de
G6	3958c	3007e	33.9a	33.9b	24 040a	21 978cd
G7	3888c	3956ab	29.9ef	30.9cde	18 864cd	17 449f
G8	4202bc	3366cde	30.5de	30.1de	18 091d	17 704ef
G9	3907c	3623bc	28.3g	30.04e	17 397d	16 178f
G10	4046c	3048de	30.5de	31.7c	20 215bc	22 409c

SCY: seed cotton yield; LL: lint length; LQI: lint quality indices. G1: Varamin; G2: Bakhtegan; G3: Sajedi; G4: Sahel; G5: T2; G6: T14; G7: Sahel × Sajedi; G8: Bakhtegan × T2; G9: Varamin × T14; G10: Sajedi × T14. Means within each column of each year followed by the same letter are not significantly different ($P < 0.05$).

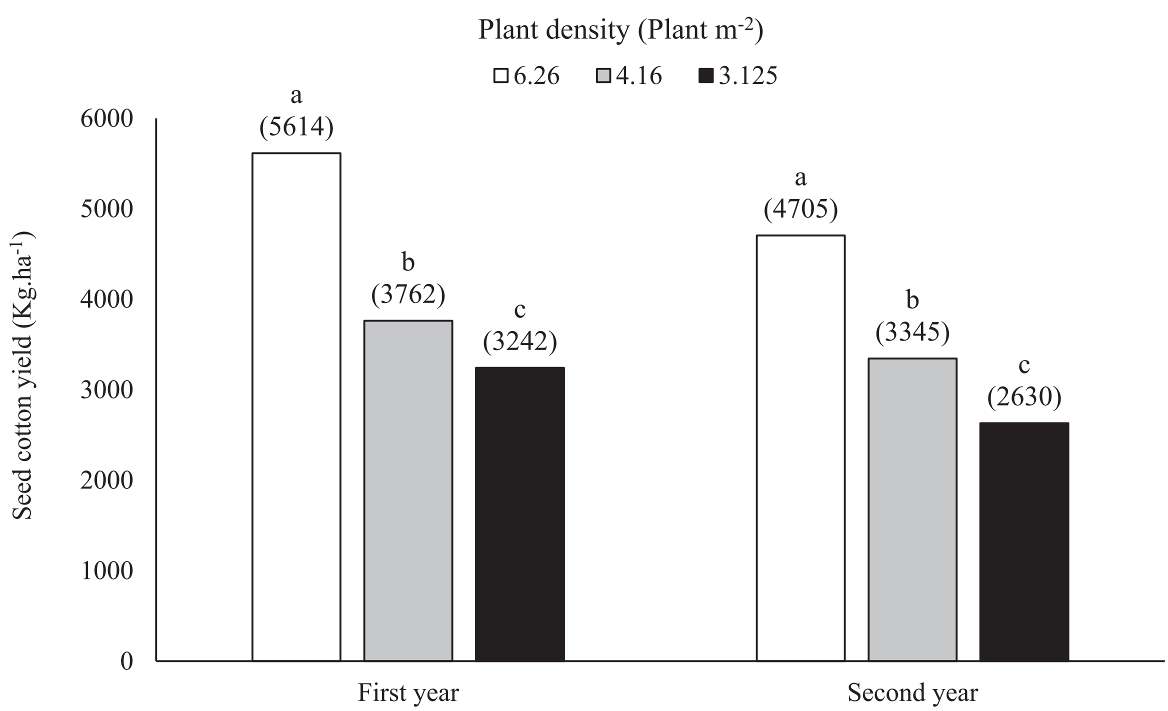

Fig. 3. Mean comparison of seed cotton yield influenced by plant density in two years. Means within each year followed by the same letter are not significantly different ($P < 0.05$).

lint length was reduced by 1.25% and 2.17% compared to moderate and lower density treatments, respectively (Tab. 3). Averaged by cotton genotypes, lint length was about 4.09% higher in 2018 than 2017 (Tab. 4). In 2017, cotton genotypes G6 (33.9 mm), G4 (33.4 mm) and G3 (32.9 mm) had higher lint length rather than other genotypes. Similar results were also achieved in 2018, in which cotton genotypes G3 (37.5 mm) and G4 (36.9 mm) produced the highest lint length. Averaged over both years, cotton genotypes G3 (35.2 mm) and G4 (35.15 mm) had the highest lint length (Tab. 4).

3.8 Lint uniformity

A significant difference ($P < 0.05$) in lint uniformity existed between years and lint uniformity in 2018 (85.1%) was significantly higher than that in 2017 (84%) by 1.29% on

Table 5. Mean comparison of the two-way interaction of plant density × genotype on lint elasticity and lint quality indices of cotton (*Gossypium hirsutum* L.).

Plant density		LE (%)	LQI
6.26 plant · m^{-2}	G1	6.95b	20 061cd
	G2	6.76bc	17 192e
	G3	6.93b	20 353cd
	G4	6.27d	26 814a
	G5	6.64c	21 308bc
	G6	5.63e	23 312b
	G7	6.95b	17 824de
	G8	6.83bc	18 398de
	G9	7.42a	16 437e
	G10	6.61c	21 807bc
4.16 plant · m^{-2}	G1	6.56de	21 348c
	G2	7.13ab	16 693e
	G3	5.93f	25 547ab
	G4	6.38e	27 214a
	G5	6.61de	20 326cd
	G6	5.46g	24 128b
	G7	6.80cd	18 211de
	G8	6.90bc	17 587e
	G9	7.29a	18 052de
	G10	6.52e	20 313cd
3.125 plant · m^{-2}	G1	6.69c	21 186
	G2	7.05ab	18 005c-e
	G3	6.18d	25 511a
	G4	5.94d	27 474a
	G5	6.54c	20 328bc
	G6	5.58e	21 586b
	G7	6.67c	18 435cd
	G8	6.79bc	17 710de
	G9	7.28a	15 874e
	G10	6.51c	21 817b

LE: lint elasticity; LQI: lint quality indices; G1: Varamin; G2: Bakhtegan; G3: Sajedi; G4: Sahel; G5: T2; G6: T14; G7: Sahel × Sajedi; G8: Bakhtegan × T2; G9: Varamin × T14; G10: Sajedi × T14. By slicing method, each studied trait in each section is separated by

average, because of higher air temperature in last two months of the growing season (Fig. 1).

3.9 Lint fineness

The results revealed that the lint fineness was significantly affected by main effect of plant densities and cotton genotypes (Tab. 1). The means comparison indicated that the lint fineness was 4.29 μg · in^{-1} under low plant density, and decreases of 3.72% and 1.65% were recorded when cotton genotypes were planted under moderate and high plant densities, respectively (Tab. 3). Cotton genotypes G6 (4.66 μg · in^{-1}) and G8 (4.54 μg · in^{-1}) had significantly higher lint fineness throughout the growing period than other genotypes during both years (Tab. 3).

3.10 Lint strength

The results showed that the main effect of year, plant densities, cotton genotypes and their interaction had significant effect on lint strength (Tab. 1). For both years, remarkable differences in lint strength averaged across the cotton genotypes were found among the plant densities. In the first year, the lint strength was the highest under low plant density for G4 (38.2 cN · tex^{-1}), G6 (37.6 cN · tex^{-1}) and G3 (36.9 cN · tex^{-1}) while under moderate and high plant density conditions, G6 (40.9 cN · tex^{-1} and 39.5 cN · tex^{-1}, respectively) had the higher lint strength (Tab. 2). Similar results were obtained in second year, in which the highest lint strength of high, moderate and low plant density was obtained in cotton genotypes of G3 (36.2 cN · tex^{-1}), G4 (37.9 cN · tex^{-1}) and G4 (36.3 cN · tex^{-1}), respectively. However, in low plant density, G3 (35.8 cN · tex^{-1}), G6 (35 cN · tex^{-1}) and high plant density, G4 (35.6 cN · tex^{-1}) and G6 (34.4 cN · tex^{-1}) were statistically at the same level (Tab. 2). Averaged across plant density treatments, G6 (39.3 cN · tex^{-1}) had the highest lint strength of first year. It should be noted that the maximum lint strength in second year (averaged by plant density) was found in G3 (36 cN · tex^{-1}) and G4 (36 cN · tex^{-1}). On average genotype treatments, lint strength in high plant density was 3.37% and 3.17% in first year, 0.8% and 0.6% lower than moderate and low plant density, respectively (Tab. 2). Averaging across years and genotype, the lint strength was 31.84 cN · tex^{-1} at high plant density and increased by 1.33% and 1.94% at moderate and low plant density.

3.11 Lint elasticity

The analysis of variance showed that effects of year, planting density, cotton genotypes, and interaction of planting density and cotton genotypes was significant on lint elasticity (Tab. 1). A significant difference in lint elasticity existed between years, and lint yield in 2018 (6.6%) was significantly higher than that in 2017 (6.5%) (Tab. 3). Cotton genotypes G6 and G9 had the lowest and highest lint elasticity compared to other genotypes under high (5.63% and 7.42%, respectively), moderate (5.46% and 7.29%, respectively) and low plant densities (5.58% and 7.28%, respectively) (Tab. 5). Under dense crops (averaged by cotton genotypes), lint elasticity was increased by 2.1% and 2.8% compared with medium (5.55%) and lower (6.51%) density crops, respectively (Tab. 5). Likewise, on averaged by plant density treatments, the highest lint elasticity was obtained in cotton genotypes G2 (6.98%) followed by G7 (6.81%) and G8 (6.84%).

3.12 LQI: lint quality indices

Different cotton genotypes had significant, while plant densities had non-significant effect on lint quality indices during both years (Tab. 1). However, significant variation between cotton genotypes × plant densities and year × cotton genotypes was found for lint quality indices. Averaged by

Table 6. Pierson correlation coefficients between yield and yield components of cotton (*Gossypium hirsutum* L.).

		BN	BW	LY	SCY	LP	LL	LU	LF	LS	LE	LQI	OS
High plant density (6.26 Plant m^{-2})	BN	1	**↓**	↑	↑	↑	**↑**	↓	**↓**	↑	↑	**↑**	↓
	BW	**↓**	1	↑	↑	↓	**↓**	↑	**↑**	↓	↓	**↓**	↑
	LY	↑	↑	1	**↑**	**↑**	↑	↓	↑	↑	**↓**	↑	↓
	SCY	**↑**	↓	**↑**	1	↓	↑	↓	↑	↓	↑	↓	↓
	LP	↓	↑	**↑**	↑	1	↑	↓	↑	↑	**↓**	**↑**	↓
	LL	↑	↑	↑	↑	↑	1	↑	↓	**↑**	↓	**↑**	↑
	LU	↓	↑	↑	↑	↑	↑	1	↓	↑	↑	↑	↑
	LF	↑	↑	↑	↑	↑	↑	↑	1	↓	↓	**↓**	↑
	LS	**↑**	↓	**↑**	↑	↑	**↑**	↑	**↑**	1	**↓**	**↑**	↑
	LE	↓	↑	**↓**	↓	↓	**↓**	↑	**↓**	**↓**	1	**↓**	↑
	LQI	↑	↓	↑	↑	↑	**↑**	↑	**↓**	**↑**	**↓**	1	↓
	OS	↑	↓	↓	↑	**↓**	↑	↑	↑	↓	↑	↓	1

		BN	BW	LY	SCY	LP	LL	LU	LF	LS	LE	LQI	OS
Medium plant density (4.16 Plant m^{-2})	BN	1	**↓**	↑	**↑**	↓	↑	↑	↑	↑	↓	↑	↑
	BW	**↓**	1	↑	↑	↑	↓	↓	↓	**↓**	↑	**↓**	↓
	LY	↑	**↑**	1	↑	**↑**	**↓**	↑	↑	↓	↑	↓	↑
	SCY	**↑**	↑	**↑**	1	**↓**	↓	↓	↓	↓	↑	↓	↑
	LP	↓	**↑**	**↑**	**↑**	1	↓	↑	↑	↓	↓	↓	↓
	LL	**↑**	↓	↑	↑	↑	1	↑	↑	**↑**	**↓**	**↑**	↑
	LU	↑	↑	↓	↑	↓	↑	1	↑	↑	↑	↑	↑
	LF	↓	↑	↓	↓	↑	↓	↑	1	↓	↑	↓	↑
	LS	**↑**	↓	↑	↑	↑	**↑**	↑	↑	1	**↓**	**↑**	↑
	LE	**↓**	↑	↓	↓	↓	**↓**	**↓**	↓	**↓**	1	**↓**	↑
	LQI	**↑**	↓	↑	↑	↓	**↑**	↑	↓	**↑**	**↓**	1	↑
	OS	↑	↓	↑	↑	↓	↓	↑	↑	↓	↑	↑	1

		BN	BW	LY	SCY	LP	LL	LU	LF	LS	LE	LQI	OS
Low plant density (3.125 Plant m^{-2})	BN	1	**↓**	↑	**↑**	↓	↑	↑	↑	↑	↓	↑	↑
	BW	**↓**	1	↑	↑	↑	↓	↓	↓	**↓**	↑	**↓**	↓
	LY	↑	↑	1	↑	**↑**	**↓**	↑	↑	↓	↑	↓	↑
	SCY	**↑**	↓	**↑**	1	**↓**	↓	↓	↓	↓	↑	↓	↑
	LP	↑	↑	**↑**	↑	1	↓	↑	↑	↓	↓	↓	↓
	LL	**↑**	↓	↑	**↑**	↓	1	↑	↑	**↑**	**↓**	**↑**	↑
	LU	↑	↑	↑	↑	↑	↑	1	↑	↑	↑	↑	↑
	LF	↓	↑	↓	**↓**	↑	↓	↑	1	↓	↑	↓	↑
	LS	**↑**	**↓**	↑	↑	↓	**↑**	↑	↓	1	**↓**	**↑**	↑
	LE	**↓**	↑	↑	↓	↑	**↓**	↓	↓	↓	1	**↓**	↑
	LQI	**↑**	↓	↑	**↑**	↓	**↑**	↑	**↓**	**↑**	**↓**	1	↑
	OS	↑	↓	↓	↑	↓	↑	↓	↓	↑	↓	↑	1

"BN: boll number $plant^{-1}$; BW: boll weight; LY: lint yield; SCY: seed cotton yield; LP: lint percentage; LL: lint length; LU: lint uniformity; LF: lint fineness; LS: lint strength; LE: lint elasticity; LQI: lint quality indices; OS: oil seed content. Bold arrows indicate a significant increase (**↑**) and decrease (**↓**), respectively. Arrow thickness indicates no significant increase (↑) and decrease (↓), respectively. The correlation coefficients in the down and upper part of the table diameter are belonged to first year and second year, respectively."

cotton genotypes, lint quality indices were about 0.83% higher in 2018 than 2017 (Tab. 4). In 2017, cotton genotypes G4 (25124) and G6 (24040) had higher lint quality indices rather than other genotypes. Similar results were also achieved in 2018, in which cotton genotypes G4 (29210) produced higher lint quality indices rather than other genotypes. Averaged over both years, cotton genotypes G4 (27167) had the highest lint length (Tab. 4). The highest and lowest lint quality indices were achieved in G4 (26814) and G9 (16437) under high plant density, G4 (27214) and G2 (16693) under moderate plant density, G4 (27474) and G9 (15874) under low plant density (Tab. 5). Under high plant density (averaged by cotton genotypes), lint quality indices were reduced by 2.8% and 2.1% compared to medium (20941.9) and lower (20792.6) plant density, respectively (Tab. 5). Likewise, on averaged by plant density treatments, the highest lint quality indices were obtained in cotton genotype G4 (27167.3).

3.13 Seed oil content

Different plant spacing had significant effect on seed oil content, while cotton genotypes or their interaction had non-significant effect on seed oil content during both years (Tab. 1). All cotton genotypes sown with 4.16 $plant \cdot m^{-2}$ resulted in higher seed oil content (16.4%) compared to 6.26 and 3.12 $plant \cdot m^{-2}$ during both years. However, there was no significant difference ($P < 0.05$) between high (14.8%) and low (15.2%) plant density (Tab. 3).

4 Discussion

In this two-year field experiment, we studied the influence of three plant densities on lint yield and yield components of ten cotton genotypes. It has been suggested that cotton genotypes should be selected for high number of bolls per unit (Ajayakumar *et al.*, 2017). Venugopalan *et al.* (2013) indicated selection for high lint yield resulted in genotypes with more boll plant^{-1} and seed boll^{-1}. Our results showed that boll plant^{-1} and seed boll^{-1} (data not shown) increased with decreasing plant density in all cultivars (Tab. 2). A likely reason for the lower boll plant^{-1} of high plant density was the reduction of carbohydrate availability caused by plant competition. At low plant density, growth resources like water and nutrients were completely utilized and plants produced more branches, resulting in a higher number of bolls plant^{-1}. Moreover, the high plant density treatment reduced the growth period to crop maturity, resulting in fewer bolls plant^{-1} initiation compared to lower plant density treatments. Indeed, excessive competition for sunlight, water and nutrients force the plants to early maturity. Presumably, high plant density lessened the sunlight penetration to canopy due to high foliage and early row closure, which causes boll abscission and lower lint quality.

Increased boll plant^{-1} in the current study with decreased plant density was offset by enhanced boll plant^{-1} resulting in increased seed number plant^{-1} (data not shown) which resulted in higher lint yield. Khan *et al.* (2019) reported that cotton planted in a 19 cm row spacing produced fewer boll plant^{-1} than cotton planted in a 38 cm row spacing. Different results for boll plant^{-1} among cotton genotypes can be primarily led different genetic diversity of plants, difference growth habits and variation in partitioning of assimilates to reproductive parts and consequently a difference in boll plant^{-1} of each genotype. Results pertaining to individual boll weight showed that high plant density negatively affected the individual boll weight related to low plant density (averaged by genotypes and two years). This corroborates the findings of Tang *et al.* (2014), who observed that the enhance of plant density reduced the boll weight plant^{-1} due to lower lint and seed mass. Darawsheh *et al.* (2009) indicated that narrow row system (high plant density) affected negatively and constantly seed weight, and the individual boll weight and its components (seed and lint).

The lint yield increase observed for cotton genotypes planted in high plant density could be attributed to more rapid canopy closure and improved soil conditions of high plant density beds in early season (Khan *et al.*, 2019; Keshavarz *et al.*, 2021b) which provided an opportunity for improved seedling percentage and probably better root system development and higher light interception, which decrease weed competition. Higher seedling percentage led to higher dry matter accumulation due to longer photosynthesis period. Luo *et al.* (2019) stated that cotton genotypes planted under low plant density did not perform well for lint yield because of high foliage and boll shedding. In fact, partitioning of assimilates into excess vegetative structures can significantly reduce cotton lint yield. Although not significant, but same results and positive correlation obtained with respect to lint yield and individual boll weight. In all plant densities, higher lint yield was positively related to the higher lint percentage (Tab. 6). The greater cotton seed yield in the plants cultivated in high population was more affected by high plant density rather than medium and low plant densities, regardless of the last two presenting higher boll plant^{-1}. Based on our results, the higher plant density compensated the fewer bolls plant^{-1}, while averaged boll weight reduced or even remained unchanged. Arunvenkatesh and Rajendran (2013) showed that highest seed cotton yield was achieved with row spacing 15 cm followed by 30 cm than 45 cm in India.

Lint quality, which depends on accumulation of cellulose in lint cell, is more sensitive to environmental factors such as humidity (Ul-Allah *et al.*, 2021), temperature (Darawsheh *et al.*, 2022), nutrient status (Gao *et al.*, 2012a, b; Wang *et al.*, 2014), plant population (as shown in our experiment) and so on. Moreover, agronomic practices and environmental factors could change cotton lint properties and carbohydrate content (Tang *et al.*, 2017; Sabourifard *et al.*, 2023). It has been reported that sucrose synthase lessened with increasing cotton population in area (Khan *et al.*, 2019). Lower sucrose synthase activity decreased availability of UDP-glucose for cellulose accumulation due to lower sucrose synthesis metabolism, which could be the reason for the lower lint formation under high plant density rather than low plant density (Ruan, 2014). It could therefore be argued that difference in plant density change the carbon translocation from source to sink, which influenced the leaf carbohydrates content and quality of lint. It has also stated that the content of polysaccharide such as fructose, glucose, sucrose and starch decreased in leaves of plant growth in high plant density (Luo *et al.*, 2019). Reduction in leaf carbohydrate content could be explained in a sense of its transposition to reproductive parts. Therefore, our results indicated that lint quality was higher in lower plant density maybe due to variation of non-structural carbohydrate under different plant density. The values of lint uniformity, lint strength and lint length are mainly affected by genotypes and environmental conditions (Tab. 6). Khan *et al.* (2019) asserted that highest lint strength and length is produced with larger cellulose molecules, lower break point and more linkages between lint. Siebert and Stewart (2006), Luo *et al.* (2019), and Jiang *et al.* (2012) also showed that plant density and lint quality are inversely related. In the present study, the increased in the lint quality under low-density treatments could be explained due to more carbohydrate sources (sucrose) to induce synthesis of free fructose and glucose. Moreover, a negative association was observed between lint percentage and lint elongation, which means that there were physiologic adjustments and down regulation partly compensate for the declined lint synthesis.

Very low or high plant density of cotton genotypes reduce seed oil percentage, since the inter-plant competition for resources (such as the availability of moisture and light) enhances with increased in dense populations, while the total number of plants per unit area decreases with wider spacing. Based on our results, seed oil content has a negative association with lint percentage (Tab. 6). The content of seed oil percentage depends on carbohydrates partitioning to two related sinks in the bolls: seeds and lint (Khan *et al.*, 2017b; Keshavarz and Khodabin, 2019). More photo-assimilates flow to seeds in combination with less photo-assimilates flow to lint could be the reason for negative correlation between lint percentage and seed oil content.

5 Conclusions

In conclusion, higher plant density ensured higher seed cotton yield, and lint elasticity in all cotton genotypes although the number of boll plant^{-1}, lint percentage and lint quality indices were reduced. However, cotton genotypes in low plant density consistently resulted less lint yield than cotton planted in the high plant density. Cotton genotypes G3, G4 and G5 resulted in higher seed cotton yield by producing higher number of bolls plant^{-1}. Yield difference among two years was derived from plant genetics, which responded differently to weather conditions. Despite the variances in the boll plant^{-1}, seed cotton yield and lint percentage among the years and genotypes, there were similarities in trends of plant density and the lint percentage, lint strength and lint quality indices increased when the plant density decreased. Among the cotton hybrids, G8 and G9 had the highest boll number and lint percentage, respectively at all plant densities. In case of lint yield, G8 had the highest lint yield, which was higher than conventional cultivars. It may be concluded from this study that high plant density systems limited yield quantity potential but enhance yield quality capacity. Thus, the results demonstrate that low plant density in Varamin may have lower seed cotton yield than cotton planted on high plant density.

Declaration of interest statement

The authors declare that they have no conflict of interest in relation to this article.

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