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Research Article

Synergistic effect of key inputs (irrigation and nutrients) on physiological behaviors and yield of upland cotton (*Gossypium hirsutum* L.)

Muhammad Akbar Zardari[1*], Aijaz Ahmed Soomro[2], Nasir Shahzad Memon[3], Azra Nadeem[4] and Robina Karim[5]
1. Agriculture Extension Wing, Agriculture Supply & Price Department, Government of Sindh, Pakistan
2. Sindh, Agriculture University, Tandojam, Sindh, Pakistan
3. On Farm Water Management Wing, Agriculture Supply & Price Department, Government of Sindh, Pakistan
4. Department of Plant Pathology, The University of Agriculture, Amir Muhammad Khan Campus, Mardan, Pakistan
5. Department of Agricultural and Applied Economics, The University of Agriculture, Amir Muhammad Khan Campus Mardan, Pakistan
**Corresponding author's email:* zardariakbar110@gmail.com

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Abstract

In order to determine the synergistic effects of key inputs (Irrigation and nutrients) on physiological behaviors and seed cotton yield of cotton, the experiments were conducted for consecutive two years (2017 and 2018). The data for both the years was pooled and effects were determined from the average data. The existing recommended dose of fertilizers (RDF) 112-56-56 kg ha^{-1} (T_2) was kept as control to investigate the crop response to 10% increase over RDF (T_1=124-62-62 kg ha^{-1}) and 10% decrease over RDF (T_3=100-50-50 kg ha^{-1}). These NPK rates were applied in integration with varied irrigation frequency such as: 7 irrigations (30, 45, 60, 75, 90, 105, 120 DAS); 6 irrigations (30, 50, 70, 90, 110, 130 DAS [existing recommendation] and 5 irrigations (30, 55, 80, 105, 130 DAS). The results showed that seed cotton yield plant^{-1} and its allied traits were significantly ($P<0.05$) affected by the interactive effect of NPK levels and irrigation frequency. The interaction of 124-62-62 kg ha^{-1} NPK × 7 irrigations resulted in slightly higher seed cotton yield plant^{-1} (141.46 g); closely followed by yield of 139.80 g and 139.44 g plant^{-1} achieved in the interactive effect of NPK at 124-62-62 kg ha^{-1} × 6 irrigations and 124-62-62 × 5 irrigations, respectively. Although, treatment interaction 124-62-62 kg ha^{-1} NPK × 7 irrigations had slight edge for seed cotton yield plant^{-1} over rest of the treatment interactions; but statistically the difference amongst 7, 6 or 5 irrigations under 124-62-62 kg ha^{-1} NPK were insignificant ($P>0.05$); suggesting that irrigating crop 7 or 6 times was uneconomical regardless of NPK application. Hence, interaction of NPK @124-62-62 kg ha^{-1} × 5 irrigations would be optimum combination to achieve economical seed cotton, seed and lint yields. However, all the physiological traits showed markedly greater values under the interaction of 124-62-62 kg ha^{-1} NPK × 7 irrigation suggestive of excessive plant growth, swelling foliage, but all these had adverse effect on seed-cotton, seed and lint yield.

Keywords: Cotton; Interactive effect NPK; Irrigation frequency; Yields, Physiological behavior

Introduction

Cotton, scientifically known as *Gossypium hirsutum* L., is an important crop for the global textile industry and has been cultivated for thousands of years for its soft, durable fibers and is a crucial and primary source of raw material for the global textile industry. This natural fiber is highly valued for its superior quality, making it the most valuable among other natural fibers. Moreover, it is the second most significant oil-seed crop worldwide [1-3]. In Pakistan cotton crop is largely cultivated for being highly lucrative crop for the production of fiber and has the potential to contribute to long-term economic prosperity of the country; because a significant portion of land is devoted to its cultivation. Hence, there has always been a lot of interest from the scientific community in studying its different aspects to improve its economic yield and fiber quality [4]. This crop has prime importance, since it is the only source of raw material for the textile industry as well as sizeable contribution to the supply of edible oil of Pakistan. Pakistan is among the top five largest cotton producing countries after China, India, USA and Brazil; cotton and its allied industries account for up to 60 percent of total overall exports of Pakistan, making significant economic drivers for the nation by 0.6% contribution to GDP. A significant decrease in area under cotton (6.8%) has been recorded due to shift of cotton area to other crops such as sugarcane, maize, potato and rice (2.079 million ha in 2020-21 to 1.937 million ha in 2021-22). Although, the crop was generally cultivated on reduced area this year, but tremendous increase in yields compensated well the challenging adverse effect of decreased area under cotton. The growers enjoyed most favorable weather this year for cotton, coupled with more consistent supply of inputs, improved crop management, and higher lint prices in local and international markets that encouraged the increased cotton production [5]. However, cotton yield is susceptible to a variety of factors, such as edaphoclimatic constraints, different genotypes, and crop management practices. These factors play a vital role in determining cotton yield and its overall quality. In addition to genotype and environmental conditions, crop management practices, including irrigation and nutrient application, play critical roles in cotton production [6].

Cotton cultivation is predominantly rain-fed in most of the producing regions of the world [7, 8]. Because of the high crop water demand, the water deficit caused by constant droughts in semi-arid regions is the main factor limiting high yields. Irrigation is important to guarantee the sustainability of production in regions most susceptible to water deficit, especially when associated with efficient water consumption and economic viability [9, 10]. However, cotton has a relatively long cycle and, when grown under full irrigation, it demands large amounts of water [11]. The average irrigation requirement for surface-irrigated cotton is reported to be 6000–7000 m^3 ha^{-1} depending on soil, weather conditions, and seasonal rainfall [12-14].

Adequate irrigation and nutrient availability are essential for plant growth and development, as they facilitate photosynthesis, nutrient uptake, and water use efficiency. The use of NPK fertilizers is crucial for the successful cultivation of cotton. N is vital nutrient for plant growth and is often the most limiting nutrient for cotton production; while P has a crucial role in energy transfer and storage, and K has essential role in plant growth, stress tolerance, and fruit development **[15]**. Similarly, irrigation is another critical factor affecting cotton growth and yield. Water stress at any stage of the crop can result in reduced fiber quality, yield, and plant growth **[16]**. Therefore, it is necessary to manage water resources efficiently to ensure the sustainable production of cotton **[17]**. examined yield and fiber quality response of cotton and reported that the integrated use of irrigation and NPK resulted in a significant increase in cotton yield and fiber quality.

Cotton plants are known for their unique physiological behaviors that allow them to grow and develop in diverse environments. Understanding the physiological behaviors of cotton is crucial for optimizing its production and improving its yield. One of the key physiological behaviors of cotton is its response to environmental cues such as light, temperature, and water availability. Cotton plants are highly responsive to changes in light, with the number of hours of daylight affecting their growth and development. For example, long-day cotton varieties require more than 12 hours of daylight to initiate flowering, while short-day cotton varieties flower with less than 12 hours of daylight **[18]**. Besides, water availability is a crucial factor in cotton growth and development, and cotton plants have been shown to be highly efficient in their water use. Cotton plants exhibit a range of morphological and physiological adaptations to water stress, including reduced leaf area, increased root density, and changes in stomatal conductance **[19]**. In addition to their responses to environmental cues, cotton plants also exhibit various internal physiological behaviors that impact their growth and development. One of the most important of these behaviors is photosynthesis, which is the process by which plants use light energy to convert carbon dioxide and water into organic compounds. Cotton plants have been shown to have a high photosynthetic rate, with their leaves exhibiting a high rate of carbon dioxide fixation **[20]**. Moreover, respiration is another important physiological behavior in cotton, and it plays a crucial role in the growth and development of the plant. Cotton plants have been shown to have a high respiratory rate, which is related to their high metabolic activity and their efficient use of resources **[21]**. Understanding the physiological behaviors of cotton is crucial for optimizing cotton production and ensuring that crop yields are maximized. By studying the physiological behaviors of cotton, researchers and farmers can develop strategies to enhance cotton production, improve crop yields, and promote sustainable agriculture **[22-25]**. This study was aimed at investigating the integrated effect of irrigation and NPK on physiological traits and yield of cotton. The findings from this study will contribute to the development of sustainable cotton production practices, which are crucial for ensuring food security and economic development in cotton-growing regions.

Materials and Methods

The study was conducted at research facilities of the Agricultural Research Center (ARC) Tandojam, Sindh. The ARC is located precisely at a latitude of 25º26'O N and a longitude of 68º32'O E. These coordinates are used to determine the geographic location of the research center on the Earth surface. The geospatial coordinates of a research center play a critical role in delineating its environmental context and climatic nuances. In 2017 and 2018, during the Kharif seasons, a cotton production experiment was conducted with the objective of investigating the combined impact of NPK fertilizers and irrigation frequency on crop physiological traits and yield. Prior to testing, the experimental land underwent a rigorous land preparation regime that included dry plowing, heavy soaking, precise levelling, and cultivator ploughing to achieve optimal seedbed conditions. The experiment utilized the Sindh-1 cotton variety, which was planted using the drilling method in Randomized Complete Block Design (factorial) with three replications. In accordance with the treatment plan, NPK fertilizers were applied at varying concentrations, and appropriate irrigation schedules were implemented. Plant protection measures were undertaken to prevent weed infestations, insect pests, and disease infections. The cotton picking was initiated when 50% of the bolls had opened, with successive harvests at 15-20 day intervals. The study results provide important insights into the optimal irrigation frequency and the appropriate dosage of NPK fertilizers for maximum cotton crop development and output.

There are various methods to determine leaf area, leaf area index, dry matter yield, NAR, CGR, and chlorophyll content in plants, including cotton. The leaf area was determined by digital imaging which involves capturing an image of the leaf and using software to calculate the area. Leaf area index was determined by Hemispherical photography which involves capturing an image of the canopy and using software to calculate the leaf area index. Dry matter yield was determined by harvesting and weighing which involves harvesting the entire plant or a subset of the plant, drying it to constant weight, and weighing it. The Net assimilation rate (NAR) was calculated as the change in dry matter weight per unit leaf area per unit time; while the crop growth rate (CGR) was determined as the change in dry matter weight per unit of existing dry matter per unit time. Similarly, the chlorophyll content by chlorophyll extraction method which involves extracting chlorophyll from a leaf sample and measuring its absorbance at specific wavelengths using a spectrophotometer. In case of yield traits, the data were recorded on the basis of five randomly selected plants. In order data on seed-cotton yield, seed yield, and lint yield achieved from randomly selected five plants in each sub-plot were achieved and calculated for the values plant^{-1} using an automatic top loading scale. First, the lint and the seed were weighed independently; and later, the weight of the lint and the weight of seed were taken together. Statistix 8.1 was used for statistical analysis of the data gathered about the interactive effect of NPK fertilizers and irrigation frequency on cotton growth and yield (Statistix, 2006). In order to find out if there were any significant difference between the treatments, the data were evaluated thoroughly. The LSD test was used to make any required comparisons of the efficacy of different treatments.

Results and Discussion

Seed-cotton yield plant^{-1}

The (Fig. 1) demonstrates the effect of treatment factors, suggested that seed cotton yield plant^{-1} was significantly ($P<0.05$) affected by NPK levels and interactive effect of NPK × irrigation regimes; while the effect of irrigation regimes did not have significant effect on seed cotton yield plant^{-1} ($P>0.05$). The results showed that treatment interaction 124-62-62 kg ha^{-1} NPK × 7 irrigations resulted in relatively higher seed cotton yield plant^{-1} of 141.46 g; followed by 139.80 g and 139.44 g seed cotton yield plant^{-1} achieved in the interactive effect of NPK at 124-62-62 kg ha^{-1} × 6 irrigations and 124-62-62 × 5 irrigations, respectively. However, least seed cotton yield plant^{-1} (116.80 g) was realized in treatment interaction of 100-50-50 kg ha^{-1} × 5 irrigations. Although, treatment interaction 124-62-62 kg ha^{-1} NPK × 7 irrigations had slight edge for seed cotton yield plant^{-1} over rest of the treatment interactions; similarity in seed cotton yield ($P>0.05$) was observed when crop was supplied with highest NPK level of 124-62-62 kg ha^{-1} and irrigation with 7, 6 or 5 irrigations. It is evident from the results that irrigating crop 7 times was uneconomical regardless of NPK application rates suggesting negative effect on the seed cotton yield ha^{-1}. However, on average 124-62-62 kg ha^{-1} NPK fertilizers proved to be effective to achieve increased seed cotton yield over the existing recommendation of 112-56-56 kg ha^{-1}; hence, 124-62-62 kg ha^{-1} NPK was an optimum level and 5 irrigations would be plenteous to maximize seed cotton yield economically. The trendline suggests that there is a general trend of decreasing yield as irrigation frequency decreases. However, the relationship is not strictly linear, as there are some points that do not follow the general trend. The coefficients of the quadratic polynomial suggest that the yield decreases as the irrigation frequency decreases, but there is an optimal irrigation frequency where the yield is maximized. The optimal frequency can be calculated by finding the maximum value of the quadratic equation (which occurs at 5-irrigations). Hence, trendline for the given data suggests that there is a negative relationship between irrigation frequency and yield, but positive relationship with the increased NPK dose and the relationship is not strictly linear and may be influenced by other factors.

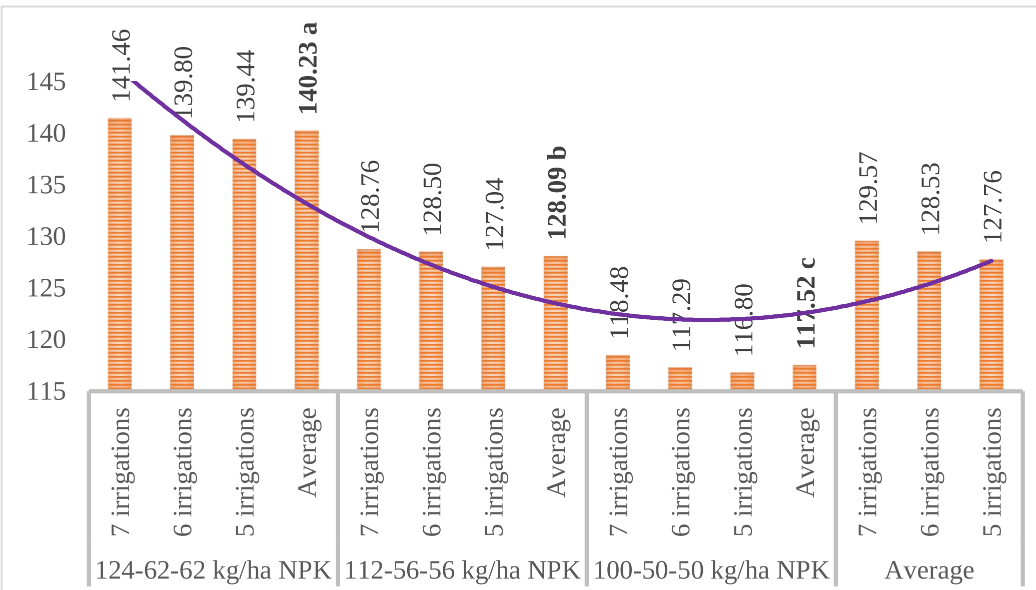

Figure 1. Response of cotton for seed-cotton yield plant^{-1} (g) to integrated effect of irrigation frequency and NPK doses

Seed yield plant^{-1}

The (Fig. 2) imitates the effect of various NPK levels and irrigation regimes as well as treatments interaction, suggesting that seed weight plant^{-1} was significantly ($P<0.05$) affected by NPK levels and interactive effect of NPK × irrigation regimes; while the effect of irrigation regimes was insignificant ($P>0.05$). The crop managed under 7, 6 and 5 irrigations resulted in average seed yield of 76.94, 76.20 and 75.82 g plant^{-1}, respectively; while average seed yield of 82.80, 75.72 and 70.44 g plant^{-1} resulted under the effect of NPK levels of 124-62-62, 112-56-56 and 100-50-50 kg ha^{-1}, respectively. It is apparent that the interactive effect of (124-62-62kg ha^{-1} NPK × 7 irrigations resulted in maximum seed yield plant^{-1} of 83.41 g; followed by 82.57 g and 82.42 g seed yield plant^{-1} achieved in the interactive effect of NPK at 124-62-62 × 6 irrigations and 124-62-62 kg ha^{-1} × 5 irrigations, respectively. However, the least seed yield plant^{-1} (69.85 g) was recorded in 100-50-50 kg ha^{-1} ×5 irrigations. Besides, the difference in seed weight plant^{-1} under the effect of irrigation regimes was non-significant. Hence, combination of highest NPK level (124-62-62 kg ha^{-1}) and 7 irrigations seems to be excessive input, because with the highest NPK level, 5 irrigation resulted in economically better seed weight plant^{-1} than those given 7 irrigations. The coefficients of the quadratic polynomial trendline for seed yield plant^{-1} suggests similarity with the trendline for seed cotton yield plant^{-1}.

Lint yield plant^{-1}

The (Fig 3). reflects the impact of different NPK levels and irrigation regimes as well as their interactions on this fiber trait in cotton. The analysis of variance indicates that lint yield plant^{-1} was significantly ($P<0.05$) affected by NPK levels and NPK × irrigation interaction; while the effect of irrigation frequency did not show significant influence on lint yield ($P>0.05$). Averagely, the crop irrigated 7, 6 and 5 times produced lint yield of 52.63, 52.33 and 51.94 g plant^{-1}, respectively. Likewise, NPK levels comprised of 124-62-62, 112-56-56 and 100-50-50 kg ha^{-1} averagely produced lint yield of 57.43, 52.37 and 47.08 g plant^{-1}, respectively. Interactive effect indicated that treatment interaction of 124-62-62 kg ha^{-1} NPK × 7 irrigations resulted in relatively higher lint yield plant^{-1} (58.05 g); showing similarity with interactions124-62-62 kg ha^{-1}NPK × 6 irrigations (57.23 g) and 124-62-62 kg ha^{-1}NPK × 5 irrigations (57.02 g); while the least lint yield plant^{-1} (46.92 g) was noted in interaction of 100-50-50 kg ha^{-1} × 6 irrigations. The 7 or 6 irrigations did not improve lint yield plant^{-1} significantly ($P>0.05$); however, the effect of NPK rates on lint yield plant^{-1} was significant ($P<0.05$). Hence, combination of highest NPK level (124-62-62 kg ha^{-1}) and 7 irrigations was not effective and highest NPK rate under 5 irrigation produced economically better results for lint yield plant^{-1} as compared to 6 or 7 irrigations. The coefficients of the quadratic polynomial trendline for lint yield plant^{-1} indicates similarity with the trendline for seed cotton yield plant^{-1}.

Ginning out-turn (%)

The (Fig. 4) suggested that the GOT was significantly influenced by different levels of NPK fertilizers and irrigation regimes × NPK level interaction ($P<0.05$); while the effect of irrigation regimes was non-significant ($P>0.05$). The crop irrigated 7, 6 and 5 times resulted in GOT was 39.03, 38.90 and 38.77 %, respectively; while crop fertilized with NPK fertilizers at the rates of 124-62-62, 112-56-56 and 100-50-50 kg ha^{-1} resulted in 39.49, 38.98 and 38.23 % GOT, respectively. The interactive effect of NPK fertilizers and irrigation regimes indicated that on average, the GOT was highest (39.69 %) when fertilized with 124-62-62 kg ha^{-1} NPK level and given 7 irrigations; followed by 39.48 and 39.30 % GOT recorded under the interactive effect of NPK at 124-62-62 kg ha^{-1} × 6 irrigations and NPK at 124-62-62 kg ha^{-1} × 5 irrigations, respectively. However, the least GOT of 38.12% was measured in the interaction of 100-50-50 kg ha^{-1} NPK × 5 irrigations. On the basis of economic importance of the results, 5 irrigations would be enough to achieve higher GOT in cotton variety Sindh-1 particularly under NPK rate of 124-62-62 kg ha^{-1}. The quadratic polynomial trendline suggests that the optimal irrigation frequency for maximum GOT% is around 4.8 irrigations (Approx. 5), and that both higher and lower irrigation frequencies can lead to lower GOT%. However, as the NPK rates increased, the GOT was also improved.

Staple length (mm)

The data for Upper Half Mean Length (UHML) or staple length demonstrated in (Fig. 5) suggested that this quality trait was significantly influenced by irrigation regimes and NPK levels ($P<0.05$); while their interaction was non-significant ($P>0.05$). The staple length in crop given 7, 6 and 5 irrigations was 23.32, 24.47 and 25.54 mm on average, while the crop fertilized with NPK at the rates of 124-62-62, 112-56-56 and 100-50-50 kg ha^{-1} resulted in staple length of 27.25, 24.53 and 21.56 mm, respectively. The interactive effect of NPK levels and irrigation regimes showed that the highest quality fiber by staple length (28.57 mm) was achieved in cotton fertilized with 124-62-62 kg ha^{-1} NPK level and given 5 irrigations; followed by staple length of 27.63mm measured in the interaction of 124-62-62 kg ha^{-1} NPK × 6 irrigations; while the least staple length (20.96 mm) was found in the interaction of 100-50-50 kg ha^{-1} NPK × 7 irrigations. It was noted that regardless of irrigation regimes, the staple length was superior in cottons given NPK fertilizers at the rates of 124-62-62 kg ha^{-1} NPK, while under recommended dose of NPK fertilizers (112-56-56 kg ha^{-1}), the staple length was significantly lower. This clearly indicates that the soils have become more deficient of essentially required elements and existing recommended dose may be revised up to 124-62-62 kg ha^{-1} NPK. However, 7 irrigations could not give desired results even under higher NPK levels, probably due to excessive moisture the plants under higher 124-62-62 kg ha^{-1} NPK grew taller and nutrients distribution caused a little adverse effect on this quality trait.

Leaf area

The (Fig. 6) represents leaf of cotton as affected by irrigation frequency and NPK interaction; and it was observed that leaf area was significantly affected by irrigation frequency, NPK levels and their interaction ($P<0.05$). The crop supplied with 7, 6 and 5 irrigations mounted resulted in average leaf area of 102.88, 98.08 and 93.96 cm^3, respectively; while NPK levels of 124-62-62, 112-56-56 and 100-50-50 kg ha^{-1} resulted in leaf area of 109.26, 98.80 and 86.86 cm^3, respectively. The study on treatment interaction showed that the leaf area maximized (115.10 cm^3) by interaction of 124-62-62 kg ha^{-1} NPK level ×7 irrigations; followed by leaf area of 109.74 cm^3 measured in the interaction of 124-62-62 kg ha^{-1} NPK × 6 irrigations; while the least leaf area (84.45 cm^3) was recorded in the interaction of 100-50-50 kg ha^{-1} NPK × 5 irrigations. The irrigation regimes had great influence on the cotton leaf area, followed by the impact of NPK levels. Regardless of irrigation regimes, the leaf area was higher in plots given NPK fertilizers at higher levels (124-62-62 kg ha^{-1}) than the existing NPK recommended dose (112-56-56 kg ha^{-1}). This clearly indicates that the soils have become more deficient of essentially required elements (NPK) and for cotton, recommended dose may be revised up to 124-62-62 kg ha^{-1}. The polynomial trend lines suggest that NPK and irrigation have significant and non-linear effects on leaf area, and their combined effect is even more complex. The data points for the highest levels of NPK and irrigation have the highest leaf area, but there may be an optimal combination of NPK and irrigation that maximizes leaf area.

Crop growth rate (CGR)

The data in regards to CGR (Fig. 7) of cotton under the influence of varied rates of NPK fertilizers and irrigation revealed that this trait was significantly affected by irrigation regimes and NPK levels ($P<0.05$); while the interactive effect of irrigation regimes × NPK levels was non-significant ($P>0.05$). The CGR of the plants receiving 7, 6 and 5 irrigations was 21.96, 20.94 and 20.06g $m^{-2}d^{-1}$, respectively; while NPK rates of 124-62-62, 112-56-56 and 100-50-50 kg ha^{-1} resulted in CGR up to 23.30, 21.09 and 18.54g $m^{-2}d^{-1}$, respectively. Interactive effect of different factors indicated that highest CGR (24.49 g $m^{-2}d^{-1}$) was determined in crop fertilized with 124-62-62 kg ha^{-1} NPK level and given 7 irrigations; followed by CGR 23.18g $m^{-2}d^{-1}$calculated from the interaction of 124-62-62 kg ha^{-1} NPK × 6 irrigations; while the least CGR (17.94 g $m^{-2}d^{-1}$) was found in the interaction of 100-50-50 kg ha^{-1} NPK × 5 irrigations. The optimum irrigation and NPK fertilizers had were the major influential elements for CGR. Even under the highest NPK level of 124-62-62 kg ha^{-1} the number of irrigations applied during the entire cotton growing season made the significant difference in the CGR. Thus, it would be right to assume that optimal use of irrigation and fertilization are mandatory to achieve desired crop growth in cotton. Based on the given data, the polynomial trend lines suggest that as the NPK fertilizer rate increases, the crop growth rate (CGR) also increases. This can be observed by comparing the average CGR values of the three NPK rates at each irrigation level. Similarly, it can be observed that as the number of irrigations increases, the CGR also increases. This trend is consistent across all three NPK rates.

Leaf area index (LAI)

The (Fig. 8) illustrates LAI of cotton as affected by irrigation frequency and nutrient levels, and portrays that irrigation regimes, NPK levels and irrigation regimes × NPK levels interaction had significant influence on LAI ($P<0.05$). The LAI of crop receiving 7, 6 and 5 irrigations was 3.93, 3.73 and 3.57, respectively; while the NPK levels of 124-62-62, 112-56-56 and 100-50-50 kg ha^{-1} resulted in the values of 4.15, 3.76 and 3.32, respectively for this trait. Treatments interaction revealed that the LAI remained highest (4.37) in the interaction of 124-62-62 kg ha^{-1} NPK level × 7 irrigations; followed by LAI 4.17 calculated in the interaction of 124-62-62 kg ha^{-1} NPK × 6 irrigations; while the lowest LAI (3.21) was calculated in the interaction of 100-50-50 kg ha^{-1} NPK × 5 irrigations. Primarily, both the factors such as irrigation frequency and NPK levels had an obvious influence on LAI. However, yield contributing traits have responded maximally to NPK fertilizers at higher levels of 124-62-62 kg ha^{-1}, but not the seven irrigations; and the response of yield contributing traits was more positive to six irrigations. However, unanimous response of growth, yield and physiological traits of cotton was against existing NPK recommended dose (112-56-56 kg ha^{-1}); and it was suggestive response to revise NPK recommendation up to 124-62-62 kg ha^{-1} for achieving desired results in cotton. Based on given data, the polynomial trend lines suggest that as the NPK fertilizer rate and irrigation frequency increased, the leaf area index (LAI) also increased and this trend is consistent across all three NPK rates.

Dry matter production

The ***(***Fig. 9***)*** displays the data on the effect of irrigation frequency and NPK levels on the dry matter (DM) production of cotton; and results indicated that irrigation frequency and NPK levels had significant effect on this parameter ($P<0.05$); while statistically the dry matter remained unaffected ($P>0.05$) by interactions of irrigation regimes × NPK levels. The DM production in crop irrigated 7, 6 and 5 times was 1250.43, 11.93 and 1143.23 g m^{-2}, respectively; while the DM production in crop receiving NPK levels of 124-62-62, 112-56-56 and 100-50-50 kg ha^{-1} remained 1328.03, 1202.17 and 1057.10 g m^{-2}, respectively. The treatment interactions comprised of 124-62-62 kg ha^{-1} NPK × 7 irrigations resulted in highest DM production (1396.3 g m^{-2}); followed by DM production of 1335.2 g m^{-2} recorded in the interaction of 100-50-50 and 124-62-62 kg ha^{-1} × 6 irrigations; while the lowest DM production (1027.6 g m^{-2}) was seen in the interaction of 100-50-50 kg ha^{-1} × 5 irrigations. There was close relationship of higher NPK levels and more frequent supply of irrigation and DM production in cotton. The crop given 7 irrigations in addition to highest NPK level of 124-62-62 kg ha^{-1} maximized the DM production apart from the results regarding

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the cotton yield and quality traits. Based on the above data, the polynomial trend lines suggested that as the NPK fertilizer level increased, the dry matter production was also increased; which can be observed by comparing the average dry matter production values of the three NPK rates at each of 3 irrigation frequencies; this trend remained consistent across all three NPK rates and irrigation frequencies.

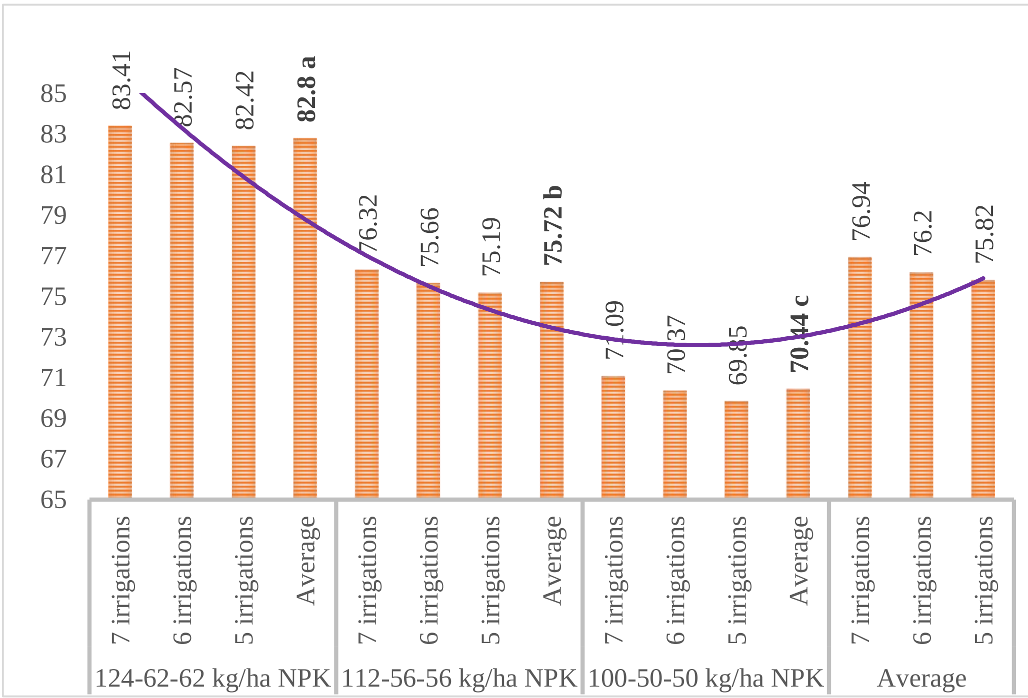

Figure 2. Response of cotton for seed yield plant^{-1} (g) to integrated effect of irrigation frequency and NPK doses

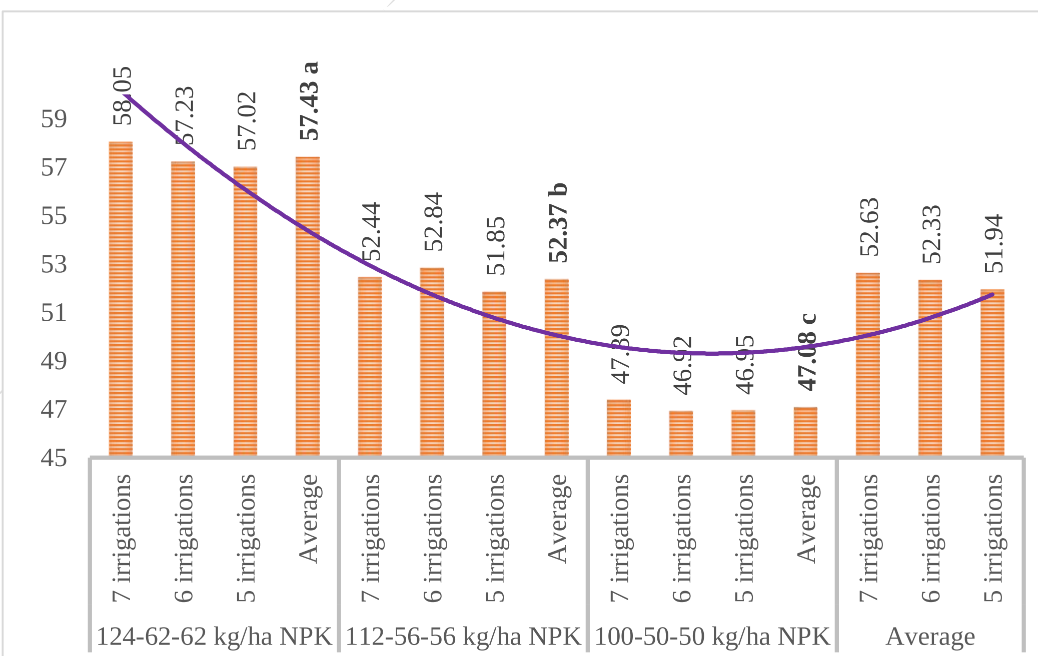

Figure 3. Response of cotton for lint yield plant^{-1} (g) to integrated effect of irrigation frequency and NPK doses

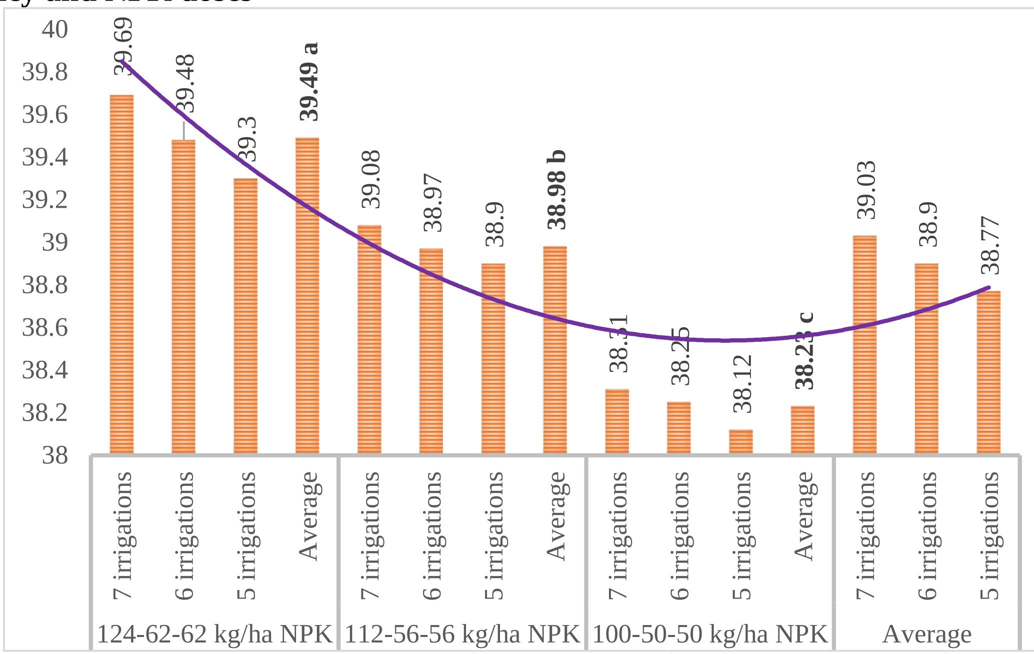

Figure 4. Response of cotton for GOT (%) to integrated effect of irrigation frequency and NPK doses

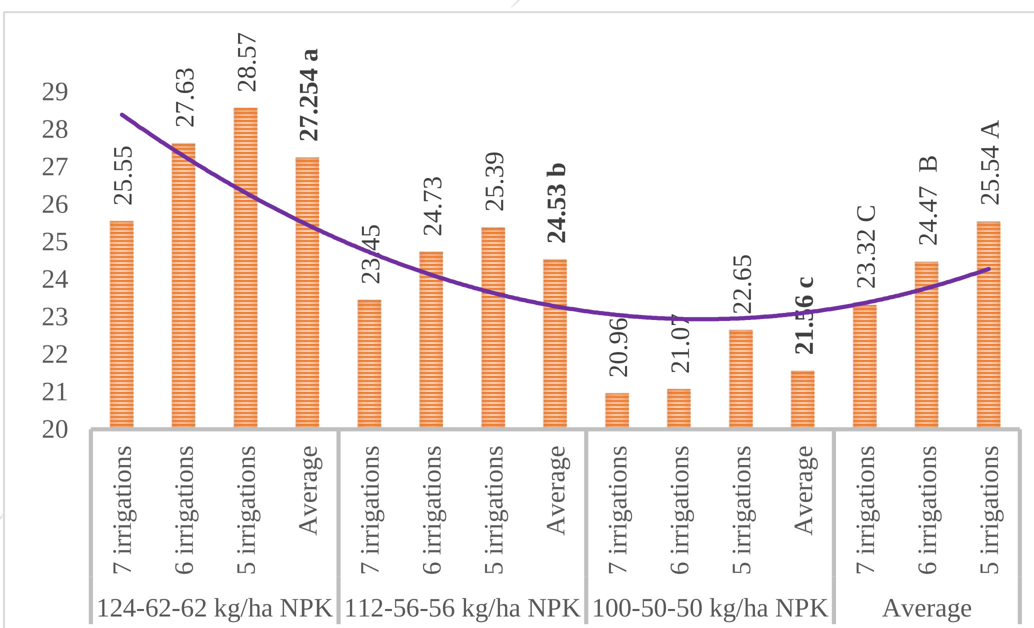

Figure 5. Response of cotton for staple length (mm) to integrated effect of irrigation frequency and NPK doses

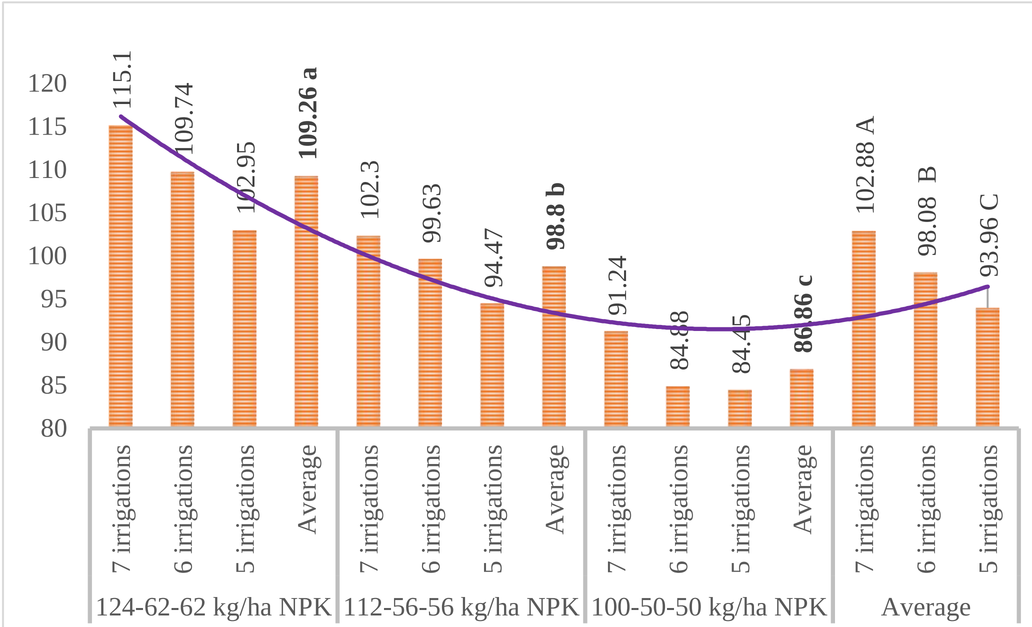

Figure 6. Response of cotton for leaf area (cm^3) to integrated effect of irrigation frequency and NPK doses

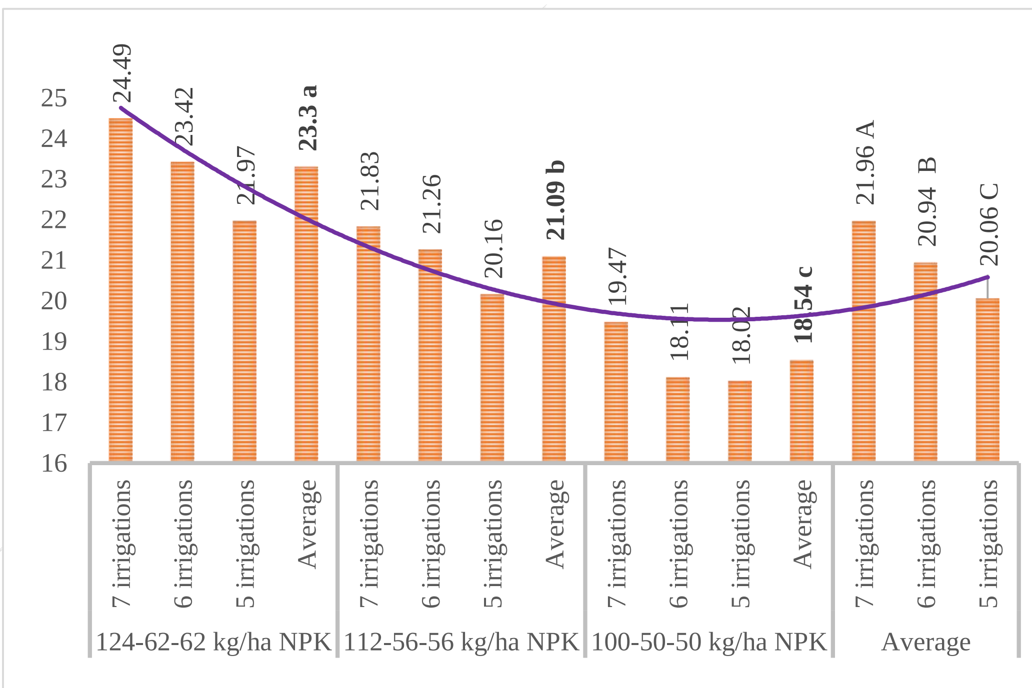

Figure 7. Response of cotton for crop growth rate (g m^{-2}d^{-1}) to integrated effect of irrigation frequency and NPK doses

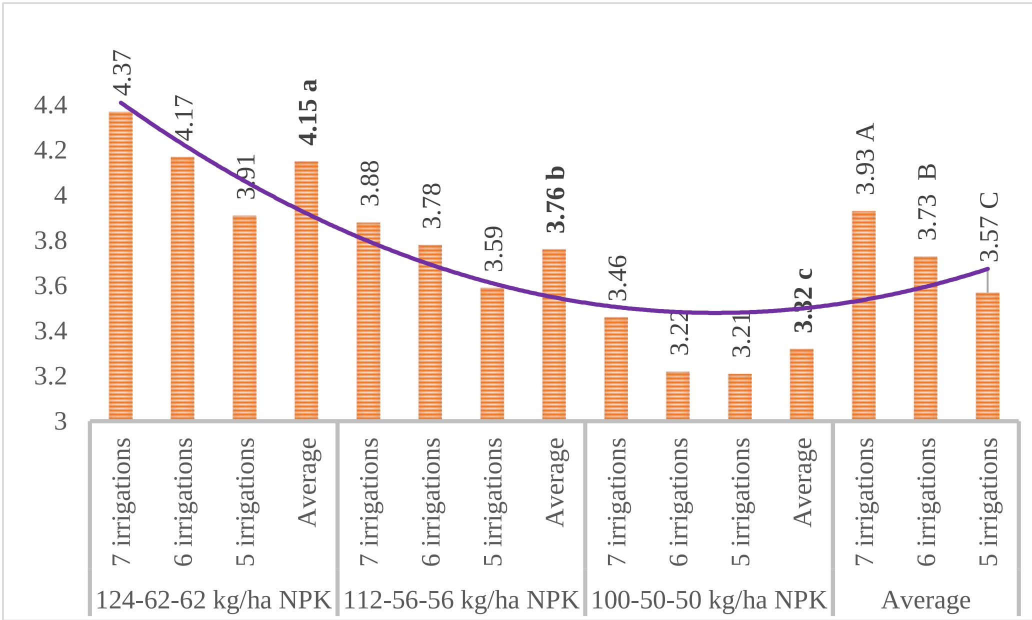

Figure 8. Response of cotton for leaf area index (LAI) to integrated effect of irrigation frequency and NPK doses

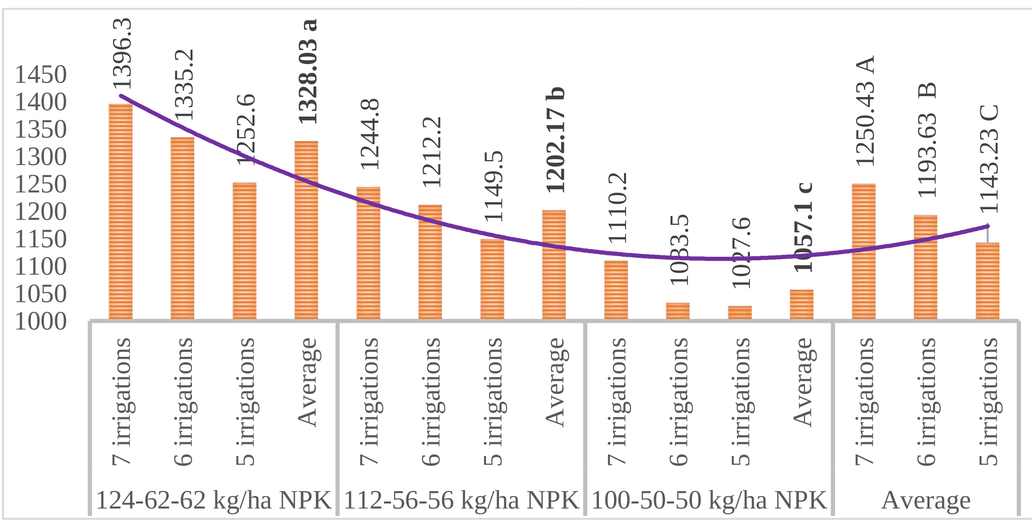

Figure 9. Response of cotton for dry matter yield (g plant^{-1}) to integrated effect of irrigation frequency and NPK doses

Chlorophyll content

Soil Plant Analysis Development (SPAD) chlorophyll meter was used to analyze greenness of cotton leaves and reading was considered as the leaf chlorophyll content. The (Fig 10) demonstrated the effect of irrigation and nutrient levels on the chlorophyll content which depicted that irrigation regimes and NPK levels had significant effect on chlorophyll content ($P<0.05$); while chlorophyll content remained unaffected statistically ($P>0.05$) by their interaction. Treatment effect showed that leaf chlorophyll content in cotton supplied with 7, 6 and 5 irrigations was 47.31, 46.36 and 45.89 rg, respectively; while the crop receiving NPK levels of 124-62-62, 112-56-56 and 100-50-50 kg ha^{-1} found to have chlorophyll content of 47.88, 46.68 and 45.00 rg, respectively. Interactive effect indicates that 124-62-62 kg ha^{-1} NPK × 7 irrigations caused highest chlorophyll content (48.68 rg); followed by chlorophyll content of 47.71 rg recorded in the interaction of 124-62-62ha^{-1} NPK × 6 irrigations; while the least chlorophyll content (44.39 rg) was determined in the interaction of 100-50-50 kg ha^{-1} × 5 irrigations. The irrigation was the major factor to develop chlorophyll content in cotton leaves, while the NPK application rate had also similar impact on this trait. The polynomial trend line suggested that the leaf chlorophyll content was relatively consistent across the three NPK rates and irrigation level. The polynomial trend line can only provide an estimation of the relationship between the variables and may not necessarily represent the true underlying relationship.

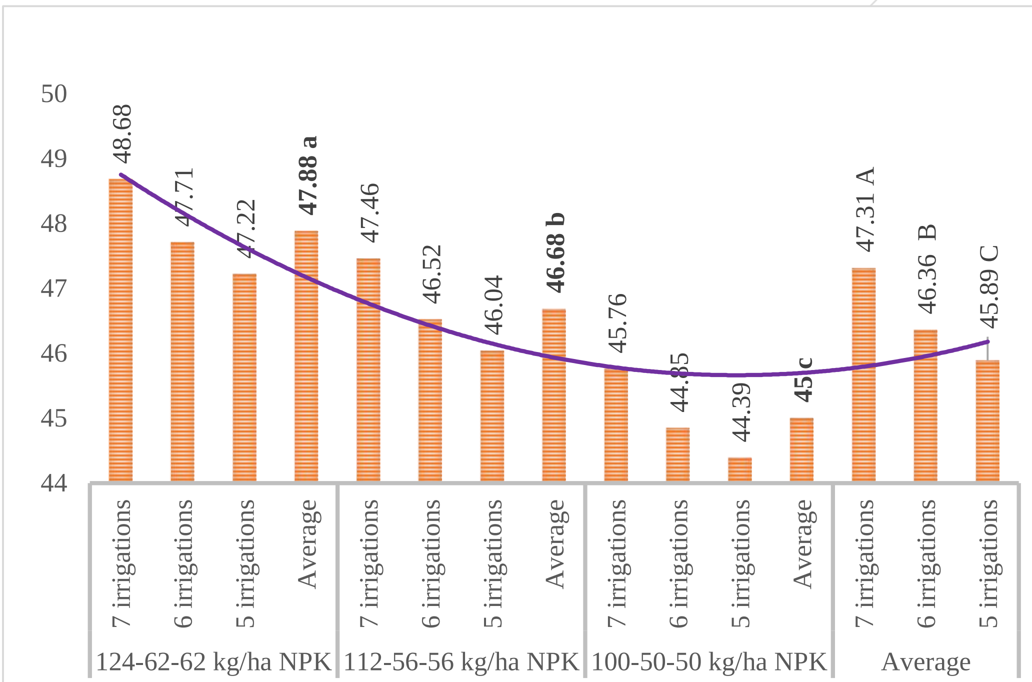

Figure 10. Response of cotton for chlorophyll content to integrated effect of irrigation frequency and NPK doses

Discussion

Irrigation and NPK fertilizers are the key inputs for cotton production, because the soils are deficient of these essentially required nutrient elements. Generally, the recommended dose of fertilizers (RDF) for the study domain is 112-56-56 kg ha^{-1} NPK, while six irrigations are recommended for desirable cotton yields. The results showed that treatment interaction 124-62-62 kg ha^{-1} NPK × 7 irrigations resulted in slightly higher seed cotton yield plant^{-1} of 141.46 g; than the yield under interactions of 124-62-62 kg ha^{-1} NPK × 6 irrigations (139.80 g) and 124-62-62 kg ha^{-1} NPK × 5 irrigations (139.44 g). However, least seed cotton yield plant^{-1} (116.80 g) was realized in treatment interaction of 100-50-50 kg ha^{-1} × 5 irrigations. Although, treatment interaction 124-62-62 kg ha^{-1} NPK × 7 irrigations had slight edge for seed cotton yield plant^{-1} over rest of the treatment interactions; but differences were non-significant (P>0.05) when seed cotton yield plant^{-1} under the interactions of 124-62-62 kg ha^{-1} NPK under 7, 6 or 5 irrigations was compared. Irrigating crop 7 times was uneconomical regardless of NPK application rates suggesting negative effect on the seed cotton yield ha^{-1}. However, on average 124-62-62 kg ha^{-1} NPK fertilizers proved to be effective to achieve increased seed cotton yield over the existing recommendation of 112-56-56 kg ha^{-1}; hence, 124-62-62 kg ha^{-1} NPK was an optimum level and 5 irrigations would be plenteous to maximize seed cotton yield economically. The trend line suggests that there was a negative relationship between irrigation frequency and yield, but positive relationship with the increased NPK dose for newly developed cotton. [26] endorsed the findings of the present research and suggested that variety specific recommendations for nutrients and irrigations need to be developed, because climatic change has developed uncertainty over the changing crop needs for essentially required inputs. [27] reported that nutrient use efficiency is the major factor to economically optimize the nutrients for cotton; and not only seed cotton yield but the lint quality must be given due consideration while fertilizer recommendations are made. [28] have suggested that the key inputs for cotton (water and nutrients) need to be evaluated frequently due to changing soil and climatic conditions. [29, 30] reported that the cotton varieties developed locally showed extended growth when watered with high frequency; due to extended growth, the boll opening is adversely affected with increased plant height. [31] found that judicious use of inputs is the real factor to influence the crop performance positively; they also suggested that variety specific production technologies would be more economical and beneficial so far the cotton cultivation is concerned. [32] have worked extensively on challenges in irrigation scheduling and suggested that latest irrigation scheduling should be modeled so that the water can be saved and applied more efficiently; because the models also provide instant information on soil, plant and weather conditions throughout the growing season and suggest irrigation to the crop accordingly. [33] have also suggested that swift change in the environmental conditions demands frequent testing of cotton varieties to optimize their input requirements.

The treatment effect on physiological traits of cotton showed relatively better performance under the treatment interaction of 124-62-62 kg ha^{-1} NPK × 7 irrigations (30, 45, 60, 75, 90, 105 and 120 DAS) with highest value for leaf area (115.10 cm^{3}), CGR (24.498 g m^{-2}d^{-1}), LAI (4.3733), TDM (1396.3 g m^{-2}) and chlorophyll content (48.687 %) measured by SPAD. The crop given 7 irrigations in addition to highest NPK level of 124-62-62 kg ha^{-1} maximized the DM production along with the values related to physiological traits, apart from the results regarding the cotton yield and quality traits. The study clearly indicates that the soils have become more deficient of essentially required elements and existing RDF has lost its validity and needs to be revised up to 124-62-62 kg ha^{-1} NPK. However, irrigation regimes based on 7 irrigations could not give desired results even under higher NPK levels, probably due to excessive moisture the plants under higher 124-62-62 kg ha^{-1} NPK grew taller bearing more bolls and nutrients distributions caused a little adverse effect on quantitative and quality traits. [34, 35] suggested that excessively improved values of physiological traits in cotton might be uneconomical in terms of seed cotton yield due to extended plant growth. They have suggested that a careful decision on the use of inputs, particularly fertilizer and irrigation water is needed for cotton, because only the optimum input rates could generate high economic returns. The study concluded that once NPK application at first flower appearance could be an optimal option to increase nutrient accumulation, achieve economically increased cotton production and without disturbing environmental factors **[36]**. **[37]** have suggested application of optimized rates of nutrients and other inputs; the environmental variation needs to be linked with the input use in cotton. The comparative analysis of achievements from the present research and relative findings reported by many researchers around the world indicated that soil type and variety specific input recommendations would be more effective and profitable for the cotton growers, rather than to adopt general recommendations for cotton.

Conclusions and Recommendations

It was concluded that the interactive effect of NPK rate of 124-62-62 kg ha^{-1} under 5 irrigations resulted in highly economical seed cotton yield, seed yield and lint yield in cotton variety Sindh-1. However, all the physiological traits showed markedly greater values under the interaction of 124-62-62 kg ha^{-1} NPK × 7 irrigation which proved excessive growth of plant increasing foliage, but adversely affecting yield traits. Considering the findings from the present research, it is recommended that for achieving economical seed cotton yield, judicious use of NPK @124-62-62 kg ha^{-1} may be ensured and five irrigations may be applied considering the critical crop stages to save the water without adverse effect on the output, particularly for newly developed cotton variety Sindh-1.

Authors' contributions

Conceived and designed the experiments: A Zardari, AA Soomro & NS Memon, Performed the experiments: A Zardari, AA Soomro, Analyzed the data: NS Memon, A Nadeem & R Karim, Contributed materials/ analysis/ tools: A Zardari, AA Soomro, Wrote the paper: NS Memon**,** A Nadeem & R Karim.

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