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Cotton Crop Improvement Through Natural Growth Enhancers

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ABSTRACT

Objective: Cotton (*Gossypium hirsutum* L.) is a major fiber and cash crop and a key component of Pakistan's agricultural economy. However, its productivity is increasingly limited by abiotic stresses that negatively affect growth, fiber quality and yield. This study aimed to evaluate the potential of selected natural growth enhancers to mitigate the adverse effects of abiotic stress on cotton growth and productivity.

Materials and Methods: The experiment was conducted at the research farm of the University of Agriculture Faisalabad, Constituent College Burewala. A randomized complete block design was employed with three replications and a net plot size of 6×9 m. Six foliar spray treatments were evaluated: control, distilled water, ginger root extract (1%), jantar leaf extract (1%), turmeric root extract (1%) and sugar beet extract (2%). Data were analyzed using Statistix 8.1 and treatment means were compared using Tukey's least significant difference (LSD) test at the 5% probability level.

Results: Foliar application of sugar beet extract at 2% significantly enhanced cotton growth and yield attributes compared with all other treatments. This treatment resulted in the highest number of bolls per plant (50.03), boll weight (5.0 g) and biological yield (11.3 t ha^{-1}), indicating superior performance in alleviating abiotic stress effects.

Conclusion: The findings demonstrate that foliar application of 2% sugar beet extract is an effective natural growth enhancer for improving cotton growth and yield under abiotic stress conditions. Its use offers an environmentally friendly and sustainable approach to enhancing cotton productivity in stress-prone agroecosystems.

INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is one of the most widely cultivated natural fiber crops worldwide and constitutes the backbone of the global textile industry[1]. In addition to fiber production, cotton is an important agricultural commodity used in the manufacture of vegetable oil and animal feed, underscoring its multifunctional economic value[2]. In many developing countries, cotton sustains the livelihoods of millions of farmers, laborers and workers engaged in processing and textile manufacturing. In Pakistan, cotton is regarded as a major cash crop and contributes substantially to national economic stability, rural employment and foreign exchange earnings[3]. A large proportion of the population depends directly or indirectly on cotton farming and its extensive value chain, encompassing production at the farm level through to finished textile products[4].

Despite its economic importance, cotton productivity is highly vulnerable to environmental stresses, particularly heat stress, which has emerged as one of the most severe abiotic constraints under changing climatic conditions[5]. Although cotton is generally classified as a heat-loving crop, exposure to temperatures exceeding its physiological thresholds can have detrimental effects on vegetative growth, reproductive development and yield formation[6]. Optimal cotton growth occurs at temperatures ranging from 20 to 30°C, whereas temperatures above 30°C especially during the reproductive phase-can result in substantial yield losses.

In cotton-producing countries such as Pakistan, summer temperatures frequently exceed 40°C, imposing extreme stress during flowering and boll development[7].

Heat stress disrupts a wide range of physiological and biochemical processes in cotton plants. Elevated temperatures adversely affect canopy development, leaf area expansion, dry matter accumulation, photosynthetic capacity and fiber quality[8]. Photosynthesis is particularly sensitive to heat stress, as high temperatures impair chlorophyll functionality, disrupt photosystem II activity and reduce enzyme efficiency, ultimately limiting carbohydrate production[9]. Reproductive structures are even more susceptible; high temperatures reduce pollen viability, retard pollen tube growth and impair fertilization, leading to increased flower and boll shedding. These adverse effects are most pronounced during flowering and boll formation, which are considered the most heat-sensitive stages of cotton development[10].

Global climate change is intensifying heat stress events in terms of their frequency, intensity and duration. Rising atmospheric temperatures, warmer night conditions and prolonged heat waves are expected to exacerbate heat stress impacts, particularly in subtropical and arid regions[11]. In Pakistan, extreme temperature episodes already contribute to poor early plant establishment, reduced fruit retention and sub-optimal fiber quality during the cotton growing season[12]. Concurrent exposure to high daytime and nighttime temperatures further aggravates respiratory losses, reduces assimilate availability, disrupts the balance between respiration and photosynthesis and ultimately lowers yield potential[13]. At present, farmers have limited effective options to mitigate the adverse effects of heat stress on cotton production.

Common management strategies include adjustments in sowing dates, increased irrigation to reduce canopy temperature, the use of early-maturing cultivars and the selection of genotypes with improved boll retention[14]. However, these approaches often involve trade-offs, such as reduced fiber quality, lower yield potential, or increased susceptibility to pests and diseases[15]. Although irrigation can partially alleviate heat stress by lowering canopy temperature, cotton plants may still experience heat injury when ambient temperatures exceed physiological limits, even under well-irrigated conditions[16]. At the physiological level, plants have evolved adaptive mechanisms to cope with heat stress, including enhanced antioxidant defense systems, maintenance of membrane stability and the synthesis of heat-shock proteins[17]. Acclimatization-defined as the adjustment of physiological processes following prolonged exposure to elevated temperatures-plays a crucial role in determining heat tolerance in plants[18].

Nevertheless, many experimental studies evaluate heat stress responses without accounting for acclimatization, which may lead to an overestimation of stress-induced damage. Elucidating the mechanisms underlying acclimation is therefore essential for identifying effective heat tolerance strategies[6]. Heat stress also markedly influences carbohydrate metabolism. Developing flowers and bolls are highly dependent on carbon assimilates supplied by subtending leaves and any disruption in carbohydrate transport or utilization can result in reproductive failure[19]. Elevated temperatures alter sugar accumulation in floral organs and ovaries, potentially causing premature abortion of reproductive structures. Although carbohydrate dynamics during anthesis under high-temperature conditions are critical, this aspect remains insufficiently explored, creating a knowledge gap in understanding the physiological basis of heat-induced yield loss in cotton[20]. Genetic improvement represents one of the most sustainable approaches to enhancing heat tolerance in cotton. While considerable variation in heat tolerance exists among cotton genotypes, the genetic basis of this variation has not been comprehensively investigated, particularly under local climatic conditions[21].

Further research is therefore required to exploit the morphological, physiological and genetic mechanisms underlying heat tolerance in order to develop resilient cotton genotypes adapted to high-temperature environments[22]. In addition to genetic strategies, the use of natural and organic growth enhancers has gained attention as an environmentally friendly approach to mitigating abiotic stress. These substances have the potential to enhance germination, improve physiological efficiency, strengthen antioxidant defense systems and support reproductive development under adverse conditions. Given the increasing frequency of heat stress events and their detrimental effects on cotton production, there is an urgent need to adopt integrated strategies to improve crop resilience[5]. Accordingly, the present study aims to evaluate the effects of different concentrations of organic growth enhancers on cotton performance from germination to maturity and to assess their potential role in enhancing growth, development and heat stress tolerance under high-temperature conditions.

MATERIALS AND METHODS

Experimental objective: The present study was undertaken to assess the effectiveness of selected natural growth enhancers applied exogenously for improving cotton growth and productivity under abiotic stress conditions.

Experimental site and design: Field experimentation was conducted at the Agronomic Research Area of the University of Agriculture Faisalabad, Constituent College Burewala, Pakistan, during the cotton growing season from July to November 2024. The experiment was laid out in a Randomized Complete Block Design (RCBD) comprising six treatments with three replications. Each experimental unit had a net plot size of 6×9 m. A heat-tolerant cotton cultivar (FH-938) was used to evaluate the response of growth enhancers under field conditions.

Land preparation and sowing: A pre-sowing irrigation of approximately 10 cm was applied to facilitate proper seedbed preparation. Once optimum soil moisture was attained, the field was cultivated four times using a tractor-mounted tiller, followed by three planking operations to achieve a fine tilth. Ridges and furrows were prepared with a tractor-mounted ridger. Cotton was sown on 15 May 2024 by manual dibbling at a depth of 3-4 cm, maintaining a row-to-row spacing of 75 cm. Prior to sowing, seeds were treated with imidacloprid (Confidor 70 WS) at a rate of 10 g kg^{-1} seed to protect against early-season sucking insect pests.

Crop management practices: Thinning was performed manually at the four-leaf stage to maintain an intra-row plant spacing of 30 cm. Pendimethalin was applied as a pre-emergence herbicide at a rate of 3.0 L ha^{-1}, followed by manual weeding and inter-culturing as required. All plots received uniform fertilizer applications, with phosphorus supplied at 60 kg ha^{-1} in the form of diammonium phosphate at sowing and nitrogen applied at 120 kg ha^{-1} as urea. Nitrogen was applied in three equal splits: At sowing, at squaring (40 DAS) and at peak flowering (70 DAS). Plant protection measures were implemented to maintain insect populations below economic threshold levels through the application of recommended pesticides. Irrigation was scheduled according to crop requirements and prevailing weather conditions, with intervals ranging from 5 to 20 days until crop maturity.

Treatments: The experiment comprised six foliar treatments designed to evaluate the efficacy of natural growth enhancers under field conditions. These included an untreated control (T_1), distilled water spray (T_2), ginger root extract at 1% concentration (T_3), jantar leaf extract at 1% (T_4), turmeric root extract at 1% (T_5) and sugar beet extract at 2% (T_6). All plant-based extracts were prepared using standard extraction protocols and stored under refrigerated conditions to preserve their bioactive constituents prior to foliar application.

Foliar application: Foliar sprays were applied manually at four critical growth stages: 35 days after sowing (post-thinning), 72 DAS (peak flowering), 98 DAS (boll formation) and 128 DAS (boll defoliation stage).

Data collection: Data were recorded following standard agronomic procedures from five randomly selected plants per plot. Observations included germination percentage, days to flowering, plant height, number of monopodial and sympodial branches per plant, number of leaves per plant, number of bolls per plant, average boll weight, seed cotton yield per plant, total seed cotton yield per hectare, biological yield and days to first flower appearance. Germination percentage was calculated as the ratio of emerged seedlings to the total number of seeds sown.

Statistical analysis: The collected data were subjected to one-way analysis of variance (ANOVA). Treatment means were compared using the Least Significant Difference (LSD) test at a 5% probability level to determine statistically significant differences among treatments.

RESULTS

Germination percentage (%): Foliar application of natural growth enhancers had no significant effect on germination percentage. This outcome was expected, as all treatments were applied after seed emergence, indicating that germination was primarily influenced by seed vigor and prevailing soil conditions rather than post-emergence foliar applications.

Plant height (cm): Plant height was significantly influenced by the foliar application of natural extracts. The tallest plants were recorded in plots treated with sugar beet extract at 2% (45.6 cm), followed by jantar leaf extract at 1% (40.3 cm), whereas the control treatment produced the shortest plants (23.1 cm). The enhanced plant height observed with sugar beet and jantar extracts may be attributed to improved nutrient availability and stimulation of cell division and elongation, resulting in enhanced vegetative growth.

Number of bolls per plant: All natural extract treatments significantly increased the number of bolls per plant compared with the control. The highest boll number was recorded with sugar beet extract at 2% (45.03), followed by jantar leaf extract at 1% (41.6), while the control exhibited the lowest boll count (24.6). The improvement in boll formation suggests enhanced flower retention and reduced reproductive abortion, likely due to improved stress tolerance and greater availability of assimilates.

Number of leaves per plant: Foliar application of natural growth enhancers markedly increased leaf production. The maximum number of leaves per plant was observed with sugar beet extract at 2% (209.6), followed by jantar leaf extract at 1% (176.3), whereas control plants produced the fewest leaves (123.3). Increased leaf number contributes to a larger photosynthetic surface area, thereby enhancing biomass accumulation.

Monopodial and sympodial branches (No.): Branching behavior was significantly affected by the application of natural extracts. Treated plants exhibited a reduction in the number of monopodial branches and a corresponding

Table 1: Effect of organic growth enhancers on cotton crop germination and phenological parameters

Treatments	Germination (%)	Plant height (cm)	No. of bolls/plant	No. of leaves per plant	No. of branches (sympodial)	No. of branches (Monopodial)
T_1	75.1	23	24.8	123.33	14.065	4.3456
T_2	77	26	27.9	128	17.776	5.0399
T_3	76.33	28	29.96	141.66	20.304	5.886
T_4	75.9	40.33	41	176.33	23.0433	6.758
T_5	75.7	37	33.067	146	21.252	6.17026
T_6	75.4	45.67	45.033	210	24.338	6.4995

Table 2: Effect of organic growth enhancers on cotton crop growth parameters

Treatments	Days to physiological maturity (days)	No. of days from emergence to flowering (days)	Leaf area index	Stem girth (cm)	Boll weight (g)
T_1	82.333	76.773	2.997	10.864	3.7442
T_2	79.667	74.49	3.151	12.827	4.1410
T_3	71	73.346	3.296	15.660	4.8060
T_4	69.2	65	3.833	20.770	5.3210
T_5	75.333	67.373	3.410	18.993	5.0610
T_6	62.333	58.96	4.236	21.319	5.5930

increase in sympodial branches relative to the control. The highest number of sympodial branches was recorded with sugar beet extract at 2% (24.3), followed by jantar leaf extract at 1% (23.04), whereas the control treatment showed the lowest value (14.03). An increase in sympodial branching is agronomically desirable, as it directly enhances boll-bearing potential and ultimately contributes to higher yield (Table 1).

Days to physiological maturity (days): As presented in Table 2, the application of natural growth enhancers significantly reduced the time required for cotton plants to attain physiological maturity. The shortest maturity period was recorded with sugar beet extract at 2% (62.2 days), followed by jantar leaf extract at 1% (69.2 days), whereas untreated plants required the longest duration to reach maturity (82.3 days). Accelerated maturity under growth enhancer treatments may be associated with improved metabolic efficiency and alleviation of stress, enabling plants to complete their life cycle more rapidly.

Days from emergence to flowering (days): Foliar application of natural extracts markedly influenced the time to flowering. Plants treated with sugar beet extract at 2% reached flowering earliest (58.96 days), followed by those receiving jantar leaf extract at 1% (65.0 days), while control plants flowered significantly later (76.7 days). Earlier flowering in response to natural extract application suggests reduced vegetative delay and enhanced physiological readiness, which may contribute to improved yield stability under stress conditions.

Leaf area index (LAI): Natural extract treatments exerted a positive effect on leaf area index (LAI). The highest LAI was recorded with sugar beet extract at 2% (4.23), followed by jantar leaf extract at 1% (3.83), whereas the lowest LAI was observed in the control treatment (2.99). An increased LAI reflects enhanced leaf expansion and canopy development, resulting in improved light interception and photosynthetic capacity.

Stem girth (cm): Foliar application of natural growth enhancers significantly increased stem girth. The greatest stem thickness was observed in plants treated with sugar beet extract at 2% (21.3 cm), followed by jantar leaf extract at 1% (20.7 cm), while control plants exhibited the smallest stem girth (10.8 cm). Increased stem girth indicates enhanced structural strength and a greater capacity for assimilate translocation.

Boll weight (g): Boll weight was significantly improved by the application of natural extracts. The highest boll weight was recorded with sugar beet extract at 2% (5.5 g), followed closely by jantar leaf extract at 1% (5.3 g), whereas control plants produced the lowest boll weight (3.7 g). Increased boll weight suggests more efficient assimilate partitioning toward reproductive sinks, contributing to improved yield performance.

Seed cotton yield (t ha^{-1}): As shown in Table 3, seed cotton yield responded significantly to the foliar application of natural growth enhancers. The highest yield was obtained with sugar beet extract at 2% (3.5 t ha^{-1}), followed by jantar leaf extract at 1% (3.1 t ha^{-1}), whereas the control treatment produced the lowest yield (1.33 t ha^{-1}). The observed yield enhancement reflects the cumulative positive effects of growth enhancers on vegetative development, boll formation and boll weight.

Biological yield (t ha^{-1}): Biological yield was significantly increased by all natural extract treatments. The maximum biological yield was recorded with sugar beet extract at 2% (11.3 t ha−1), followed by jantar leaf extract at 1%

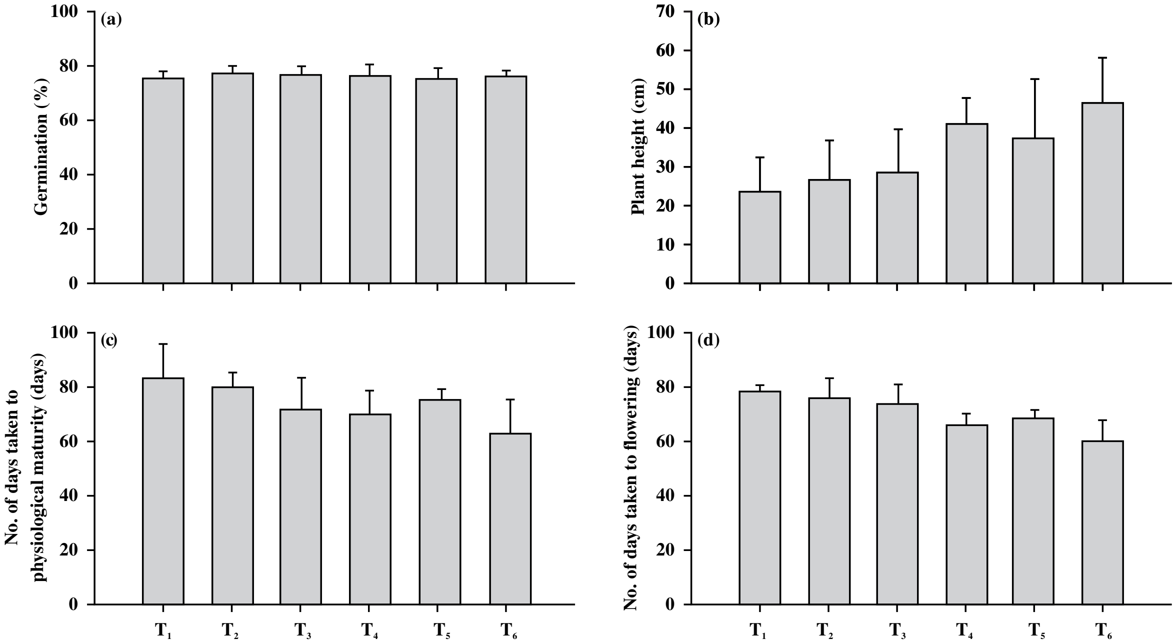

Fig. 1(a-d): A comparative analysis of three key agronomic parameters (germination percentage, plant height and phenological development) across six experimental treatments
T_1: Control, T_2: Distilled water, T_3: Ginger root extract 1%, T_4: Janter leaf extract 1%, T_5: Turmeric root extract 1% and T_6: Sugar beet extract 2%

Table 3: Effect of organic growth enhancers on cotton crop yield parameters

Treatments	Seed cotton yield (t/ha)	Biological yield (t/ha)	Harvest index (%)
T_1	23.2428	5.8250	1.3550
T_2	27.1120	6.0330	1.6616
T_3	25.5120	8.2166	2.0430
T_4	30.3640	10.3630	3.1700
T_5	29.6005	8.8660	2.6350
T_6	31.2785	11.3500	3.5750

(10.30 t ha⁻), while untreated plants exhibited the lowest biomass production (5.8 t ha^{-1}). Increased biological yield indicates improved vegetative growth and overall plant vigor under growth enhancer application.

Harvest index (%): Harvest index was not significantly influenced by the foliar application of natural extracts. Although both biological and seed cotton yields increased, the proportion of total biomass allocated to economic yield remained relatively constant across treatments. This indicates that natural growth enhancers promoted vegetative and reproductive growth in a proportional manner without altering biomass partitioning efficiency.

Figure 1 shows that germination percentage varied from 0 to approximately 16%, indicating substantial differences in seed viability and early seedling establishment among treatments. Plant height exhibited pronounced treatment-dependent variation, ranging from about 20 cm to nearly 80 cm, reflecting differential effects of the applied treatments on vegetative growth.

Phenological development was evaluated using two indicators: Days to flowering and days to physiological maturity. The time required to reach flowering varied widely among treatments, spanning approximately 20 to 100 days, while the duration to physiological maturity extended to nearly 80 days. Collectively, these findings demonstrate that the applied treatments exerted a marked influence on germination performance, vegetative growth vigor and the timing of reproductive development in the studied system. Figure 2 shows the four yield-related parameters across six treatments. Figure 3 presents two critical harvest metrics across six treatments.

DISCUSSION

The present study demonstrates that foliar application of natural growth enhancers significantly improved cotton growth, phenological development and yield performance under field conditions, with sugar beet extract at 2% showing superior efficacy compared with other treatments. The pronounced effectiveness of sugar beet extract may be attributed to its rich composition of bioactive compounds, including soluble sugars, amino acids, betaines and essential micronutrients, which collectively enhance metabolic activity and improve plant adaptability to abiotic stress[23]. These constituents likely function as biostimulants,

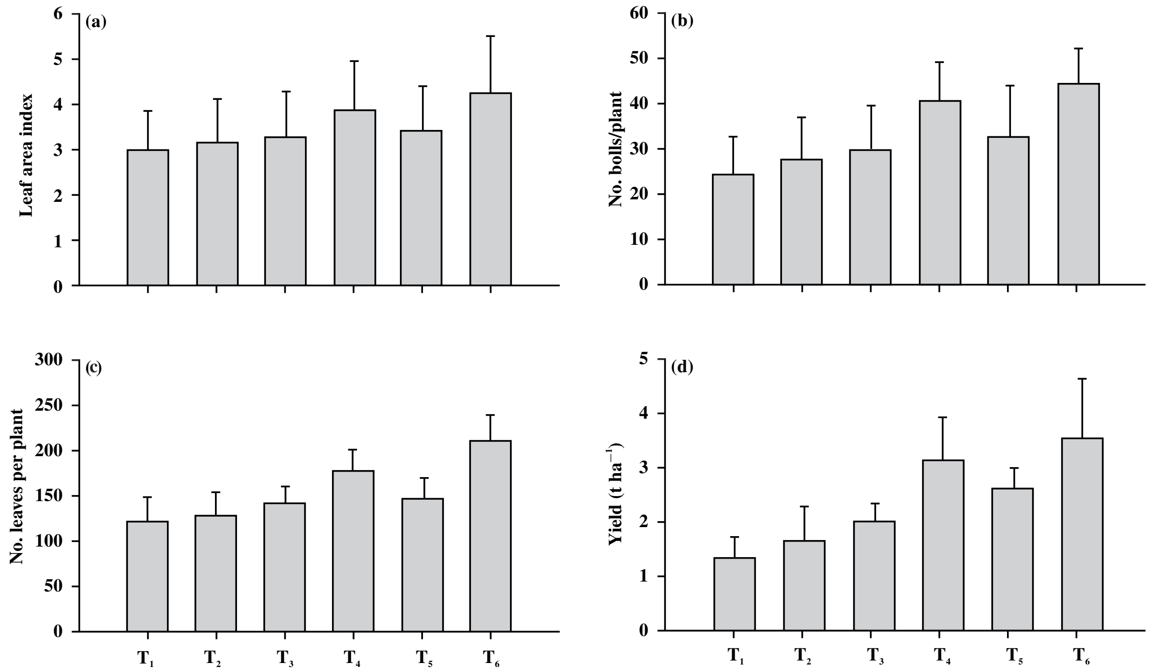

Fig. 2(a-d): Four yield-related parameters across six treatments
T_1: Control, T_2: Distilled water, T_3: Ginger root extract 1%, T_4: Janter leaf extract 1%, T_5: Turmeric root extract 1% and T_6: Sugar beet extract 2%). The Leaf Area Index (LAI) and the number of leaves per plant quantify canopy development and photosynthetic potential. The number of balls (likely bolls or pods, depending on the crop) per plant represents the reproductive output. Finally, the overall agronomic performance is summarized by the yield in tons per hectare. The clustered bars allow for a direct comparison of how each treatment influences vegetative growth, reproductive capacity and final economic yield

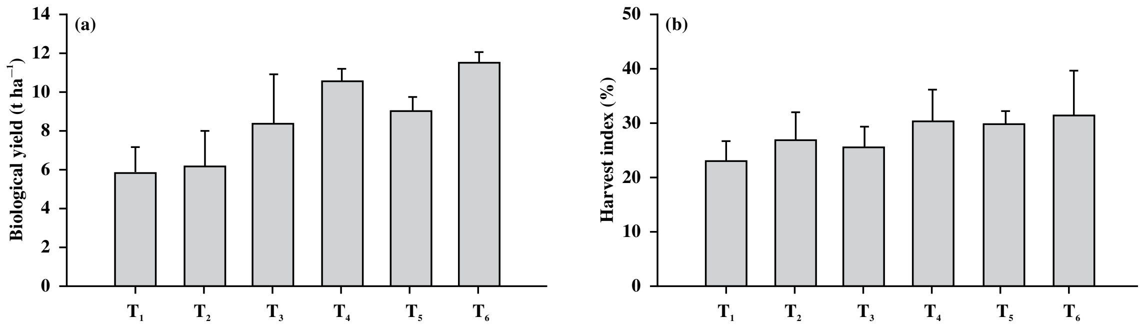

Fig. 3(a-b): Two critical harvest metrics across six treatments
T_1: Control, T_2: Distilled water, T_3: Ginger root extract 1%, T_4: Janter leaf extract 1%, T_5: Turmeric root extract 1% and T_6: Sugar beet extract 2%). The biological yield (in tons per hectare) represents the total above-ground dry matter production. The harvest index (expressed as a percentage) quantifies the proportion of the biological yield that is constituted by the economically valuable grain or seed yield. The side-by-side presentation of these bars allows for the assessment of treatment effects on both overall biomass accumulation and the partitioning efficiency of assimilates into the harve stable product

enhancing physiological efficiency and enabling cotton plants to better withstand stress conditions prevalent during the growing season. Germination was not affected by foliar treatments, as applications were made post-emergence; however, significant improvements in subsequent vegetative and reproductive traits indicate that natural extracts primarily influence post-establishment growth rather than early seedling development[23].

Enhancements in plant height, leaf number and leaf area index observed under sugar beet and jantar leaf extract treatments reflect improved cell division, cell elongation and expansion of photosynthetically active surfaces. Increased canopy development likely facilitated greater light interception and assimilate production, which is particularly important under heat stress conditions where photosynthetic efficiency is often constrained[24]. Furthermore, earlier flowering and a reduced time to physiological maturity observed in treated plants indicate accelerated phenological progression, reflecting improved metabolic efficiency and stress mitigation. Advancing the onset of flowering through sugar beet extract application may reduce the exposure of sensitive reproductive stages to prolonged heat stress, thereby improving flower retention and boll formation. Such phenological adjustments are especially advantageous in heat-prone agroecosystems, where delayed development often results in substantial yield penalties[25].

Natural growth enhancers also markedly improved reproductive performance, as evidenced by increased sympodial branching, higher boll numbers and greater boll weight. The increased number of sympodial branches under sugar beet extract application suggests a shift toward a more productive plant architecture, as sympodial branches directly bear fruiting structures[26]. Enhanced boll retention and increased boll weight further indicate more efficient assimilate partitioning toward reproductive sinks, likely due to improved carbohydrate availability and translocation under biostimulant application. The combined improvement in vegetative growth, reproductive efficiency and biomass accumulation under sugar beet and jantar leaf extracts underscores their cumulative positive effects on cotton productivity[27].

The increase in biological yield observed in treated plants reflects improved overall vigor and more efficient resource utilization, while the unchanged harvest index indicates that natural growth enhancers promoted vegetative and economic yields proportionally without altering biomass partitioning patterns[28]. Such a balanced growth response is agronomically desirable, as excessive vegetative growth without corresponding yield gains can be detrimental in cotton. Overall, the findings highlight the potential of sugar beet extract as an environmentally friendly and sustainable growth regulator for cotton under abiotic stress conditions[2]. Its ability to enhance physiological performance, promote favorable phenological development and improve yield attributes suggests that natural biostimulants can effectively complement conventional agronomic practices. Further research is warranted to elucidate the underlying biochemical and molecular mechanisms and to optimize application rates and timings across diverse agro-climatic environments.

CONCLUSION AND FUTURE PROSPECTS

The present study demonstrates that natural growth enhancers can be effectively applied exogenously to improve cotton growth, phenological development and yield performance under abiotic stress conditions. Among the evaluated treatments, foliar application of sugar beet extract at 2% consistently produced superior outcomes by enhancing vegetative growth, accelerating flowering and physiological maturity, increasing sympodial branching and improving boll formation, boll weight, as well as seed cotton and biological yields. These improvements indicate enhanced physiological efficiency, more effective assimilate partitioning and improved stress tolerance, without adversely affecting biomass allocation, as evidenced by the unchanged harvest index. The use of sugar beet extract as a plant-based biostimulant therefore represents a sustainable and environmentally friendly approach to mitigating heat-induced yield losses in cotton production systems.

Further research is required to elucidate the underlying physiological, biochemical and molecular mechanisms through which sugar beet extract enhances stress tolerance, including its effects on antioxidant activity, osmolyte accumulation, hormonal regulation and carbohydrate metabolism. To ensure the reliability, scalability and broader applicability of these findings, multi-location and multi-season trials across diverse agro-climatic conditions are warranted. In addition, optimization of application timing, dosage and integration with genetic improvement and agronomic management practices will be essential to fully realize the potential of natural growth enhancers in enhancing cotton resilience and productivity under increasingly variable climatic conditions.

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