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Influence of conventional and nano fertilizers on growth, yield, quality traits, and economics of Bt cotton

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ABSTRACT

Cotton (Gossypium hirsutum L.) is one of the most important fibre crops, contributing significantly to the textile industry and rural economy of India. Enhancing its productivity requires balanced and efficient nutrient management, and the use of nano-fertilizers has recently emerged as a promising alternative to conventional fertilization. A field experiment was conducted during Kharif 2023 at AICRP on Cotton, Chamarajanagar, to study the effect of conventional and nano fertilizers on a Bt-cotton hybrid. The experiment was laid out in a split plot design with three replications, comprising three levels of conventional fertilizers in the main plot (50 %, 75 % and 100 % RDNP) and four dosages of nano fertilizers in the subplot (nano urea @ 2- and 4-mL L^{-1}, nano DAP @ 2- and 4-mL L^{-1}), sprayed at 40, 60 and 80 DAS. The results revealed that among the conventional fertilizer levels, application of 100 % RDNP recorded significantly higher growth attributes, including plant height (172.7 cm), number of sympodial branches (31.8 plant^{-1}), and total dry matter production (326.32 g plant^{-1}). Yield attributes such as total number of bolls (47.3 plant^{-1}), good opened bolls (42.2 plant^{-1}), and seed cotton yield (1453 kg ha^{-1}) were also superior in this treatment, along with maximum gross returns (₹1,23,491 ha^{-1}) and net returns (₹47,049 ha^{-1}). Among nano fertilizers, foliar application of nano DAP @ 4 mL L^{-1} at 40, 60 and 80 DAS resulted in higher plant height (197.4 cm), number of sympodial branches (31.1 plant^{-1}), total dry matter production (369.86 g plant^{-1}), total number of bolls (46.7 plant^{-1}), good opened bolls (41.9 plant^{-1}), and seed cotton yield (1420 kg ha^{-1}), with gross returns (₹1,20,709 ha^{-1}) and net returns (₹43,049 ha^{-1}). The study faced challenges such as variability in nutrient uptake efficiency and the limited field validation of nano-fertilizers under diverse soil and climatic conditions, which may influence the consistency of results. Nevertheless, it contributes valuable insights by demonstrating that both conventional and nano fertilizers play a significant role in improving growth, yield, and economic returns of Bt-cotton, with 100 % RDNP and nano DAP @ 4 mL L^{-1} showing promising results for sustainable nutrient management.

Keywords: *Bt-cotton, Nano fertilizers, Conventional fertilizers, Growth and yield, Net returns, B: C ratio, Nutrient management, Input use efficiency, Seed cotton yield, Dry matter accumulation.*

1. Introduction

Cotton (*Gossypium hirsutum* L.) is one of the most important economic crops globally, playing a central role in both agricultural production and the textile industry [52]. It provides raw material for the textile sector, oilseed for edible oil extraction, and cottonseed cake for livestock feed, thus contributing to multiple sectors of the economy. Cotton cultivation is widely distributed across tropical and subtropical regions of more than 80 countries, serving as a primary source of livelihood for millions of smallholder farmers [26,44]. Due to its enormous economic and social importance, cotton is often referred to as "White Gold," symbolising its value to both global agriculture and industry [37]. Globally, the major cotton-producing countries include India, China, the United States, Brazil, Pakistan, and Uzbekistan, which together contribute over 80 % of world production [20].

Among these, India and China are the largest producers, accounting for more than half of global cotton output [12]. Cotton has unique socio-economic importance, particularly in developing countries where it generates significant employment opportunities in cultivation, processing, and textile industries [5].

The introduction of Bacillus thuringiensis (*Bt*) cotton in the late 1990s marked a breakthrough in pest management, particularly against bollworms, which had historically been the most damaging pest in cotton production [27]. In China, *Bt* cotton has been cultivated since 1997, with the area under cultivation expanding rapidly to 3.8 million hectares by 2007, accounting for 69 % of the national cotton-growing area. By 2018, *Bt* cotton covered nearly 95% of the total cotton area in the country [19,52]. India approved *Bt* cotton hybrids in 2002, leading to widespread adoption and a transformation of the cotton sector. Today, India is the world's largest cotton-growing country, cultivating about 12.9 million hectares annually [3,23]. The adoption of *Bt* cotton has helped in reducing insecticide use, increasing productivity, and improving farm profitability [27]. However, certain *Bt* cotton varieties have shown a tendency

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towards premature senescence, leading to yield reductions of 10–30 % [52].

India's cotton sector has a pivotal role in the national economy, as nearly 65% of the country's textile industry depends on cotton [20]. Cotton is cultivated on a vast area of 12.9 million hectares, producing around 3.3 million bales, with an average productivity of 442.65 kg ha^{-1} [3,12]. In Karnataka alone, cotton is cultivated on about 949,000 hectares, producing nearly 251,300 bales with an average yield of 460.02 kg ha^{-1} [3]. Despite being the largest cultivator of cotton globally, India's productivity is considerably lower than that of other major producing countries, such as China and the USA, where yields exceed 1,000 kg ha^{-1} [12]. Low productivity in India is attributed mainly to the fact that nearly 70 % of the crop is grown under rainfed conditions, exposing it to abiotic stresses such as erratic rainfall, drought, and poor soil fertility [5,16]. Biotic stresses, including pests and diseases, also continue to challenge cotton farmers, despite the adoption of *Bt* hybrids.

Among the various production constraints, nutrient management plays a central role in determining yield and fibre quality. Nitrogen (N) is particularly important in cotton growth and development, as it is directly involved in protein synthesis, chlorophyll formation, boll setting, and fibre elongation [11]. However, the efficiency of conventional nitrogen fertilizers is relatively low, with only 30–50 % of applied nitrogen being taken up by crops. The remainder is lost through leaching, volatilisation, and denitrification, leading to reduced crop performance and significant environmental issues, including groundwater contamination and greenhouse gas emissions [28,34,40]. Phosphorus (P) is another critical nutrient for cotton, playing a vital role in energy transfer, root development, and boll formation. However, in conventional fertilization practices, a large proportion of phosphorus becomes fixed in the soil, reducing its availability to plants [42]. To address these inefficiencies, the focus has shifted towards innovative solutions such as nano-fertilizers. Nano-fertilizers are engineered materials with particle sizes typically less than 100 nm, designed to improve nutrient use efficiency, reduce losses, and provide controlled and sustained nutrient release [32]. They offer a higher surface area-to-volume ratio, better solubility, and enhanced interaction with plant tissues compared to conventional fertilizers [37]. Studies have demonstrated that foliar application of nano-urea and nano-DAP can significantly improve nutrient uptake, reduce fertilizer requirement, and sustain yields in cotton and other crops [7,33].

Nano urea, a liquid nitrogen fertilizer developed by the Indian Farmers Fertiliser Cooperative (IFFCO), has shown promising results in reducing fertilizer consumption. A 500 mL bottle of nano urea has been reported to replace a conventional 45 kg bag of urea, potentially reducing nitrogen fertilizer needs by 50 % [21]. This innovation addresses both economic concerns for farmers and environmental issues linked to excessive nitrogen use. Similarly, IFFCO has recently launched Nano DAP (Diammonium Phosphate), comprising 8 % nitrogen and 16 % phosphorus, which has been reported to enhance nutrient absorption, improve photosynthetic activity, and increase crop yields [22]. These innovations align with sustainable agricultural practices, as they reduce dependency on conventional fertilizers, minimize environmental damage, and improve input-use efficiency.

Integrating nano-fertilizers with conventional fertilization strategies in cotton cultivation offers a promising pathway towards sustainable intensification. By improving nutrient use efficiency and reducing fertilizer losses, farmers can achieve higher yields and better fibre quality while reducing production costs. Thus, the combined use of nano and conventional fertilizers holds significant potential for improving the productivity, profitability, and sustainability of *Bt* cotton cultivation in India and globally.

2. Material and Methods

2.1 Experimental site

The field experiment was conducted during *Kharif* 2023 at the AICRP on Cotton, Haradanahalli Farm, Chamarajanagar, Karnataka. The site falls under the Southern Dry Zone (Zone-6) and is geographically located at 11.9261° N latitude, 76.9437° E longitude, with an altitude of 865 m above mean sea level.

2.2 Soil characteristics of the experimental site

2.2.1 Soil sampling

Representative soil samples were collected from the experimental plot before sowing at a depth of 0–15 cm using a screw auger. The samples were thoroughly mixed to form a composite sample (~500 g), air-dried, ground, and sieved through a 2 mm sieve. The processed samples were used for physical and chemical analysis as per standard procedures.

2.2.2 Soil characteristics

The soil of the experimental site was sandy loam in texture with 56.93 % sand, 13.89 % silt, and 29.18 % clay. Bulk density was 1.41 g cm^{-3}. The soil was alkaline in reaction (pH 8.62), medium in electrical conductivity (0.31 dS m^{-1}), and medium in organic carbon content (0.59 %). It was low in available nitrogen (242.79 kg ha^{-1}), medium in available phosphorus (48.74 kg ha^{-1}), and medium in potassium (202.59 kg ha^{-1}).

Soil pH and EC were determined by potentiometric and conductometric methods, respectively [24]. Organic carbon was estimated by [48] wet oxidation method. Available nitrogen was determined using the alkaline potassium permanganate method [41], phosphorus by the Olsen extractant method [24] and potassium by flame photometry [24].

2.3 Climatic conditions

2.3.1 Normal climate

The experimental site normally receives an annual rainfall of about 809.28 mm with a bimodal distribution. The first peak occurs in April–May and the second in September–October. The highest and lowest mean maximum temperatures were recorded in April (36.4 °C) and October (31.4 °C), respectively, while mean minimum temperatures were highest in July (20.2 °C) and lowest in January (11.4 °C). The highest relative humidity was observed in October (91.9 %), while the lowest was in March (30.4 %).

2.3.2 Actual weather during experimentation

During *Kharif* 2023, the total rainfall received was 523.6 mm, below normal. The highest rainfall occurred in May (299.0 mm) and the lowest in December (9.0 mm). Mean maximum temperatures ranged from 29.0 °C (July) to 34.3 °C (April), while mean minimum temperatures ranged from 12.7 °C (January) to 21.2 °C (September). Relative humidity ranged between 97–100 % (maximum) and 52–65 % (minimum) during July–December 2023.

2.4 Experimental details

2.4.1 Design and layout

The experiment was laid out in a split-plot design with three replications. The main plots consisted of three levels of conventional fertilizers (50 %, 75 %, and 100 % RDNP), while the subplots included four foliar sprays of nano-fertilizers:

- Nano urea @ 2 ml L^{-1}
- Nano urea @ 4 ml L^{-1}
- Nano DAP @ 2 ml L^{-1}
- Nano DAP @ 4 ml L^{-1}

In total, 12 treatments were tested. Each block represented a replication, separated by 1.0 m. Main plots were separated by 0.5 m and further split into subplots. Bunds (30 cm height) were raised between plots to avoid nutrient flow.

2.5 Crop management

2.5.1 Seeds and sowing

Certified seeds of *Bt* cotton hybrid *Ambari-2110* were sown on 16th July 2023 at a seed rate of 1.25 kg ha^{-1}. Two seeds per hill were dibbled at a spacing of 90 cm × 60 cm. Gap filling was performed 10 days after sowing, and thinning was carried out at 15 DAS to retain one healthy plant per hill.

2.5.2 Fertilizer application

The recommended dose of fertilizer (150:75:75 kg N:P_2O_5: K_2O ha^{-1}) was applied as per the UAS (B) package of practices. Full phosphorus and potassium were applied basally, while nitrogen was applied in four equal splits:

- Basal,
- 50 DAS (grand growth stage),
- 80 DAS,
- 110 DAS.

Nano-urea (2- and 4-ml L^{-1}) and nano-DAP (2- and 4-ml L^{-1}) foliar sprays were imposed as per treatments at 40, 60, and 80 DAS.

2.5.3 Irrigation

First irrigation was given immediately after sowing to ensure uniform germination. Subsequent protective irrigations were scheduled based on soil moisture and crop requirements.

2.5.4 Intercultural operations

Weeding was performed manually at 20, 40, and 60 DAS, followed by hoeing. Earthing-up was carried out at 60 DAS to support crop growth.

2.5.5 Plant protection

Plant protection measures were adopted as per the UAS (B) package of practices. For bollworm and sucking pest management, the following sprays were applied:

- Fipronil 5 % SC @ 1 ml L^{-1} at 40 DAS,
- Confidor 17.8 % SL @ 0.5 ml L^{-1} at 65 DAS,
- Emamectin benzoate 5 % SG @ 1 g L^{-1} at 100 DAS.

2.6 Observations and data collection

Growth observations (plant height, number of sympodial branches, and dry matter accumulation) were recorded at 30, 60, 90, 120, 150 DAS, and at harvest. Yield parameters (number of bolls, boll weight, seed cotton yield) were recorded at harvest.

2.6.1 Fibre quality parameters

The Quality parameters such as Ginning percentage and Lint index (g) were calculated by using the following formulas-

$$\text{Ginning percentage} = \frac{\text{Weight of lint (g)}}{\text{Weight of seed cotton (g)}} \times 100$$

$$\text{Lint index} = \frac{\text{Weight of 100 seeds} \times \text{Ginning percentage}}{100 - \text{Ginning percentage}}$$

2.6.2 Economics

The benefit-cost ratio was calculated as:

Benefit cost ratio was worked out by using the following formulaB: C ratio = Gross returns (Rs. ha^{-1}) Total cost of cultivation (Rs. ha^{-1})

2.7 Statistical analysis

The experimental data were analyzed using analysis of variance (ANOVA) following Fisher's method as outlined by [15]. Treatment differences were tested at 5 % level of significance. In case of significant results, Critical Difference (CD) at 5 % was computed. Correlation studies on growth, yield, quality, and economics were performed using R software (integrated with Python).

3 Results and Discussion

3.1 Growth Attributes

The application of conventional and nano fertilizers significantly influenced the growth parameters of *Bt* cotton, including plant height, number of monopodial branches, number of sympodial branches, length of sympodial branches, and leaf area (Table 1). Among the conventional fertilizer treatments, the application of 100 % Recommended Dose of Nitrogen and Phosphorus (RDNP) recorded superior growth attributes, with plant height (172.7 cm), number of monopodial branches (2.8 $plant^{-1}$), number of sympodial branches (31.8 $plant^{-1}$), length of sympodial branches (30.4 cm), and leaf area (105.79 cm^2 $plant^{-1}$). The improvement in growth under higher fertilizer doses may be attributed to the greater availability of nutrients, which enhanced physiological processes and facilitated the translocation of photosynthates to meristematic tissues. Similar findings were reported by [4, 35, 39] who observed that effective nutrient management, particularly phosphorus, improves the diversion of plant metabolites and enhances photosynthate movement to sink tissues, thereby promoting the development of monopodial branches. The increased metabolic and physiological activities, including higher chlorophyll synthesis and cell multiplication, further contributed to enhanced leaf area development.

Among the nano-fertilizer treatments, foliar application of nano DAP at 4 ml L^{-1} applied at 40, 60, and 80 DAS produced the highest growth values, recording plant height (197.4 cm), number of monopodial branches (3.2 $plant^{-1}$), number of sympodial branches (31.1 $plant^{-1}$), length of sympodial branches (33.6 cm), and leaf area (104.35 cm^2 $plant^{-1}$). The improved growth response can be attributed to the critical role of phosphorus in nucleic acid synthesis, energy transfer, and metabolic functions that support photosynthesis and overall plant development [1]. Similar results were reported by [6] who found that nano-fertilizer sprays accelerate nutrient uptake and increase efficiency, resulting in improved plant height and vigor. Phosphorus also directs photosynthates toward reproductive growth, enhancing cell division and elongation, which increases the number of sympodial branches [38]. Furthermore, foliar nutrient application enhances auxin production and amino acid synthesis, leading to greater leaf proliferation and expanded leaf area, corroborating the findings of [31,46]. Overall, the results clearly indicate that higher conventional fertilizer levels and nano DAP foliar sprays significantly improved the growth attributes of *Bt* cotton, with nano-fertilizer application showing a pronounced advantage in enhancing nutrient-use efficiency and plant vigor.

3.2 Dry Matter Production

The accumulation of dry matter in *Bt* cotton was significantly influenced by both conventional fertilizer levels and foliar sprays of nano fertilizers (Table 2). Among the conventional fertilizer treatments, the application of 100 % Recommended dose of Nitrogen and Phosphorus (RDNP) recorded the highest dry matter production in leaf (73.95 g plant^{-1}), stem (136.48 g plant^{-1}), reproductive parts (115.89 g plant^{-1}), and total dry matter (326.32 g plant^{-1}). The enhanced dry matter accumulation can be attributed to the role of nitrogen in increasing photosynthetic efficiency, promoting leaf expansion, and improving leaf longevity. Since leaf area expansion is highly responsive to nitrogen supply, sufficient nitrogen availability supports higher leaf dry matter through greater chlorophyll formation and photosynthetic activity. Similar observations were reported by [47] who noted that adequate nutrient availability improves uptake and utilization, leading to enhanced physiological processes and the efficient translocation of photosynthates to meristematic tissues. Phosphorus also plays a vital role in metabolite absorption, water uptake, and energy transfer, thereby promoting plant growth [14]. These nutrients enhance cell division, elongation, and critical biochemical processes, including respiration and enzymatic reactions, which contribute to increased root growth and vegetative branching [2]. Likewise, [17] emphasized the synergistic role of NPK fertilizers in dry matter accumulation, highlighting nitrogen's role in leaf growth and protein synthesis and phosphorus's contribution to root development both essential for sustained photosynthetic activity.

Foliar application of nano DAP at 4 ml L^{-1} at 40, 60, and 80 DAS recorded the maximum dry matter accumulation across plant parts, with leaf (89.04 g plant^{-1}), stem (145.11 g plant^{-1}), reproductive parts (135.70 g plant^{-1}), and total dry matter (369.86 g plant^{-1}). The superior performance of nano fertilizers can be attributed to their higher surface reactivity, nanoscale size, and enhanced nutrient-use efficiency, which improve phosphorus absorption and facilitate better root activity. [45] reported that nano fertilizers promote root proliferation, thereby improving water and nutrient uptake, which in turn enhances metabolic activity and dry matter accumulation. Similarly, [30] observed significant improvements in fresh and dry plant weight under nano fertilizer applications due to enhanced meristematic activity. [13] further highlighted that nanoparticles can alter gene expression and metabolic pathways, positively influencing plant growth and biomass production. Increased nutrient bioavailability from nano fertilizers supports chlorophyll formation, enhances photosynthetic efficiency, and ultimately leads to higher dry matter accumulation, as corroborated by [18] Overall, the findings clearly indicate that while higher conventional fertilizer doses improved dry matter accumulation, foliar application of nano DAP at 4 ml L^{-1} was more effective, suggesting its potential as a sustainable strategy for enhancing nutrient-use efficiency and maximizing biomass production in *Bt* cotton.

3.3 Yield Attributes

The yield attributes of *Bt* cotton were significantly influenced by both conventional fertilizer levels and foliar applications of nano fertilizers (Table 3). Among the conventional fertilizer treatments, the application of 100 % RDNP recorded the maximum total number of bolls (47.3 plant^{-1}) and good opened bolls (42.2 plant^{-1}), while the lowest number of bad opened bolls was observed (5.1 plant^{-1}). The enhancement in yield traits can be attributed to the positive influence of nitrogen in stimulating vegetative growth, improving nutrient uptake, and facilitating metabolite accumulation. These processes reduce abscission of squares and bolls, thereby improving boll retention. Similar results were reported by [25,27] who noted that adequate nitrogen supply reduces fruiting body shedding. The favorable moisture availability during critical growth stages may have also contributed to the increased number of well-developed bolls [34].

This treatment also produced the highest single boll weight (6.18 g) and seed cotton yield (1453 kg ha^{-1}). The improvement in boll weight and yield may be attributed to the availability of higher phosphorus levels during boll development, which enhances assimilate translocation and metabolic activity. [9] similarly observed that phosphorus application supports boll filling and seed development. The application of the full NPK dose (150:75:75 kg ha^{-1}) likely stimulated essential physiological processes, promoted chlorophyll formation, and improved photosynthate allocation to developing sinks. These findings corroborate [14] who reported that higher nutrient availability enhances both growth and yield parameters in cotton.

With respect to nano fertilizers, foliar application of nano DAP at 4 ml L^{-1} at 40, 60, and 80 DAS produced a higher number of bolls (46.7 plant^{-1}) and good opened bolls (41.9 plant^{-1}), while reducing the number of bad opened bolls (4.8 plant^{-1}). This improvement can be attributed to the enhanced absorption efficiency of nano fertilizers, which facilitates better nutrient use efficiency and rapid uptake by leaves. Foliar-supplied nano nitrogen also increased the photosynthetic rate, leading to greater dry matter accumulation, which in turn provided assimilates for boll development. These results are in accordance with [9,11,13].

The highest boll weight (6.16 g) and seed cotton yield (1420 kg ha^{-1}) were also achieved with nano DAP at 4 ml L^{-1}. The contribution of phosphorus in nucleic acid synthesis, cell structure formation, and energy transfer is crucial for reproductive growth and yield. [1] highlighted that phosphorus enhances photosynthesis and overall plant metabolism, leading to improved boll retention and weight. Moreover, [6] emphasized that nano fertilizers improve nutrient uptake efficiency, which positively influences both vegetative and reproductive growth. Overall, the results demonstrated that while conventional fertilizer at 100 % RDNP ensured maximum yield attributes, foliar application of nano DAP at 4 ml L^{-1} produced nearly comparable outcomes, underscoring its potential as a sustainable and efficient nutrient management strategy in *Bt* cotton cultivation.

3.4 Quality Parameters

The quality attributes of *Bt* cotton, namely seed index, lint index, and ginning percentage, were significantly influenced by both conventional and nano fertilizer treatments (Table 4).

Application of 100 % RDNP recorded a higher seed index (12.04 g), lint index (7.10), and ginning percentage (36.75 %).

The improvement in these parameters may be attributed to the role of phosphorus in chlorophyll biosynthesis, enhanced mobilization of photosynthates, and increased boll weight, which collectively contribute to higher seed index values. Similar observations were reported by [18,19] The higher nitrogen levels under this treatment likely enhanced phosphorus uptake, which is essential for fat biosynthesis through glycerophosphate formation, thereby improving fibre quality. These findings are consistent with [43]. Moreover, the positive effects of fertilizers on RNA synthesis, leading to increased protein formation and improved fibre properties, were also highlighted by [8].

Among the nano fertilizer treatments, foliar application of nano DAP at 4 ml L^{-1} at 40, 60, and 80 DAS resulted in the highest seed index (12.22 g), lint index (7.46 g), and ginning percentage (37.07 %). This enhancement is attributed to the improved photosynthetic efficiency and metabolic activities facilitated by nano fertilizers, which promote protein synthesis and various biochemical processes during the reproductive phase. Such improvements significantly contribute to better fibre development. These results corroborate the findings of [49,50] who reported that nano fertilizers enhance physiological efficiency and fibre properties. Furthermore, the accumulation of dry matter in cotton fibres and the enhanced deposition of cellulose in the secondary cell wall, as described by [19,34] , may have further contributed to improved fibre indices.

Regarding fibre technological properties, such as fibre length, fibre strength, fibre fineness, and uniformity ratio, no significant differences were observed among treatments with either conventional or nano fertilizers. Application of 100 % RDNP recorded maximum fibre length (34.55 mm), fibre strength (35.08 g tex^{-1}), fibre fineness (2.74 micronaire), and uniformity ratio (86.33). Similarly, foliar application of nano DAP at 4 ml L^{-1} registered fibre length (34.50 mm), fibre strength (35.33 g tex^{-1}), fibre fineness (2.79 micronaire), and uniformity ratio (86.44). These results indicate that fibre quality traits are relatively less influenced by nutrient management and are more strongly determined by genetic and varietal factors. Comparable observations were made by [10] who emphasized that fibre quality characteristics are largely under genetic control, with minimal variation due to fertilization. Overall, the findings suggest that while conventional and nano fertilizers improve seed and lint indices and ginning percentage, fibre technological properties remain predominantly stable, highlighting the varietal influence on these traits.

3.5 Economics

The economic performance of *Bt* cotton was significantly influenced by the application of conventional and nano fertilizers (Table 5). Among the conventional fertilizer treatments, the application of 100 % RDNP recorded the highest gross returns (Rs. 123,491 ha^{-1}) and net returns (Rs. 47,049 ha^{-1}) compared to other fertilizer levels. This superior economic outcome can be attributed to the enhanced growth and yield parameters, which led to increased dry matter production and photosynthetic efficiency. As a result, there was greater synthesis and allocation of photosynthates towards seed cotton production, culminating in higher seed cotton yield and subsequently, higher returns. Similar findings were reported by [29,46] who observed that improved nutrient management directly contributed to increased productivity and profitability. Furthermore, the highest benefit-cost ratio (B:C ratio) of 1.56 was recorded in the same treatment, indicating the economic feasibility of applying 100 % RDNP. The observed differences in B: C ratio across treatments are primarily attributed to variations in yield and input costs, as supported by the work of [25].

With respect to foliar application of nano fertilizers, nano DAP at 4 ml L^{-1} resulted in the highest gross returns (Rs. 120,709 ha^{-1}), net returns (Rs. 43,049 ha^{-1}), and B: C ratio (1.56) among all foliar treatments. The superior performance was linked to improvements in key growth traits such as leaf area per plant, number of monopodial and sympodial branches, total dry matter production, total number of bolls, and single boll weight. These physiological enhancements contributed to improved seed cotton yield, thereby increasing overall profitability. These findings align with those of [29] who emphasized that effective nutrient management, including foliar sprays, leads to increased productivity and economic returns.

Furthermore, the interaction effects between conventional and nano fertilizers were found to be statistically non-significant for all the measured parameters in this study, suggesting that each factor independently influenced growth and yield without synergistic interactions.

In conclusion, both conventional and nano fertilizer treatments significantly improved the economics of *Bt* cotton cultivation, with 100 % RDNP and foliar nano DAP at 4 ml L^{-1} emerging as the most cost-effective treatments for maximizing returns.

3.6 Correlation Analysis

The correlation analysis conducted using Python (Fig.1) revealed several significant relationships among the growth, yield, quality, and economic traits of *Bt* cotton. Both positive and negative associations were observed, highlighting how various plant characteristics interact and influence productivity.

3.6.1 Growth Traits:

Plant height exhibited a moderate positive correlation with the number of monopodial branches (r = 0.71), the number of sympodial branches (r = 0.44), and the length of sympodial branches (r = 0.73). These relationships suggest that taller plants are more likely to develop additional branches and longer sympodial shoots, contributing to increased canopy spread and photosynthetic capacity.

3.6.2 Biomass Accumulation:

Total dry matter production was strongly associated with its individual components. It showed a very high correlation with leaf dry matter (r = 0.94), stem dry matter (r = 0.90), and reproductive dry matter (r = 0.94), indicating that an increase in vegetative and reproductive organs collectively enhances total biomass accumulation.

3.6.3 Yield Traits:

Yield parameters were positively correlated with several key traits. Single boll weight (r = 0.53), number of good opened bolls (r = 0.62), and total number of bolls (r = 0.58) demonstrated moderate positive correlations with yield, underscoring their critical roles in determining final seed cotton production. Conversely, poorly opened bolls were negatively correlated with yield parameters (r = -0.60), suggesting that greater boll shedding or damage adversely affects productivity.

3.6.4 Quality Traits:

Seed index (r = 0.39) and lint index (r = 0.58) showed positive associations with ginning percentage, indicating that improvements in seed and lint characteristics enhance fibre processing efficiency.

3.6.4 Economic Traits:

Yield was strongly correlated with economic returns, with a perfect positive correlation with gross returns (r = 1.00), a nearly perfect correlation with net returns (r = 0.99), and a very high correlation with the benefit-cost ratio (r = 0.97). This emphasizes that higher yields directly translate into greater profitability.

These results illustrate how improvements in growth traits lead to greater biomass production, which subsequently enhances yield and economic benefits. The analysis also highlights the detrimental impact of poorly developed bolls on yield, while quality traits such as seed and lint indices contribute positively to processing efficiency.

Future line of work:

1. Effect of nutrient levels and nano fertilizer on yield and fibre quality under different planting geometry.
2. Need to study long term effect of nano fertilizers on *Bt* cotton and other cotton varieties.
3. Need to study seed priming with nano structured slow-release fertilizers.

Table 1: Growth parameters of Bt cotton as influenced by different levels of conventional and nano fertilizers, Kharif 2023

Treatments		Plant height (cm)	Monopodial branches (No plant^{-1})	Sympodial branches (No plant^{-1})	Length of sympodial branches (cm)	leaf area (cm^2 plant^{-1})
Main plot: Conventional fertilizer (M): 03						
M_1	50 % of recommended N and P kg ha^{-1}	156.3 ± 21.2	2.4 ± 0.18	26.5 ± 7.11	27.1 ± 1.69	77.67 ± 25.00
M_2	75 % of recommended N and P kg ha^{-1}	160.9 ± 37.08	2.6 ± 0.13	28.9 ± 15.45	29.0 ± 3.13	94.41 ± 16.33
M_3	100 % of recommended N and P kg ha^{-1}	172.7 ± 29.08	2.8 ± 0.25	31.8 ± 2.60	30.4 ± 4.18	105.79 ± 14.5
S.Em ±		2.54	0.02	0.79	0.33	1.51
CD (p=0.05)		9.97	0.09	3.11	1.31	5.95
Sub plot: Spraying of Nano fertilizer (S): 04						
S_1	Nano urea at 2 ml L^{-1} @ 40, 60 and 80 DAS	143.6 ± 4.25	2.2 ± 0.06	26.6 ± 1.80	26.4 ± 2.56	78.69 ± 6.11
S_2	Nano urea at 4 ml L^{-1} @ 40, 60 and 80 DAS	149.0 ± 7.43	2.4 ± 0.18	28.8 ± 2.02	27.4 ± 2.30	89.28 ± 14.64
S_3	Nano DAP at 2 ml L^{-1} @ 40, 60 and 80 DAS	163.1 ± 9.58	2.6 ± 0.15	29.7 ± 3.26	27.8 ± 0.46	98.19 ± 18.69
S_4	Nano DAP at 4 ml L^{-1} @ 40, 60 and 80 DAS	197.4 ± 17.18	3.2 ± 0.47	31.1 ± 3.82	33.6 ± 2.46	104.35 ± 18.55
S.Em ±		3.84	0.11	0.53	0.68	2.54
CD (p=0.05)		11.40	0.32	1.57	2.02	7.55
Interaction (MxS)						
S.Em ±		6.65	0.19	0.91	1.18	4.38
CD (p=0.05)		NS	NS	NS	NS	NS

Table 2: Dry matter production and partioning in different parts of Bt cotton as influenced by different levels of conventional and nano fertilizers, Kharif 2023

Treatments		Leaf dry matter (g plant^{-1})	Stem dry matter (g plant^{-1})	Reproductive dry matter (g plant^{-1})	Total dry matter production (g plant^{-1})
Main plot: Conventional fertilizer (M): 03					
M_1	50 % of recommended N and P kg ha^{-1}	54.79 ± 42.66	124.87 ± 25.04	99.21 ± 6.45	278.88 ± 52.90
M_2	75 % of recommended N and P kg ha^{-1}	65.02 ± 15.11	127.18 ± 26.57	103.29 ± 18.63	295.49 ± 59.84
M_3	100 % of recommended N and P kg ha^{-1}	73.95 ± 55.25	136.48 ± 42.24	115.89 ± 33.11	326.32 ± 129.49
S.Em ±		2.77	6.32	2.17	4.99
CD (p=0.05)		10.86	5.27	8.51	19.60
Sub plot: Spraying of Nano fertilizer (S): 04					
S_1	Nano urea at 2 ml L^{-1} @ 40, 60 and 80 DAS	45.61 ± 6.88	119.10 ± 3.15	86.29 ± 2.27	251.00 ± 7.11
S_2	Nano urea at 4 ml L^{-1} @ 40, 60 and 80 DAS	53.16 ± 7.44	121.25 ± 9.42	95.98 ± 4.91	270.38 ± 17.66
S_3	Nano DAP at 2 ml L^{-1} @ 40, 60 and 80 DAS	70.53 ± 3.16	132.58 ± 6.63	106.55 ± 9.17	309.67 ± 16.72
S_4	Nano DAP at 4 ml L^{-1} @ 40, 60 and 80 DAS	89.04 ± 24.61	145.11 ± 22.44	135.70 ± 19.80	369.86 ± 65.46
S.Em ±		4.39	5.59	3.31	11.04
CD (p=0.05)		13.05	16.61	9.84	32.80
Interaction (MxS)					
S.Em ±		7.61	9.68	5.74	19.12
CD (p=0.05)		NS	NS	NS	NS

Table 3: Yield and yield parameters in Bt cotton as influenced by different levels of conventional and nano fertilizers, Kharif 2023

Treatments		Good opened bolls (No plant^{-1})	Bad opened bolls (No plant^{-1})	Total Number of bolls (plant^{-1})	Single boll weight (g)	Seed cotton yield (kg ha^{-1})
Main plot: Conventional fertilizer (M): 03						
M_1	50 % of recommended N and P kg ha^{-1}	33.1 ± 10.61	7.7 ± 1.75	40.8 ± 9.54	5.50 ± 0.9	1194 ± 186.38
M_2	75 % of recommended N and P kg ha^{-1}	35.3 ± 2.56	7.2 ± 1.28	42.5 ± 1.55	5.83 ± 1.17	1315 ± 157.36
M_3	100 % of recommended N and P kg ha^{-1}	42.2 ± 6.64	5.1 ± 0.97	47.3 ± 4.03	6.18 ± 1.18	1453 ± 357.38
S.Em ±		0.96	0.19	0.81	0.08	30.92
CD (p=0.05)		3.77	0.76	3.18	0.33	121.41
Sub plot: Spraying of Nano fertilizer (S): 04						
S_1	Nano urea at 2 ml L^{-1} @ 40, 60 and 80 DAS	31.7 ± 4.93	9.7 ± 0.19	41.4 ± 3.20	5.65 ± 0.30	1231 ± 114.46
S_2	Nano urea at 4 ml L^{-1} @ 40, 60 and 80 DAS	35.1 ± 4.62	7.2 ± 2.01	42.3 ± 2.67	5.73 ± 0.32	1295 ± 117.81
S_3	Nano DAP at 2 ml L^{-1} @ 40, 60 and 80 DAS	38.2 ± 7.28	6.1 ± 0.32	44.3 ± 3.83	5.80 ± 0.32	1336 ± 148.53
S_4	Nano DAP at 4 ml L^{-1} @ 40, 60 and 80 DAS	41.9 ± 5.97	4.8 ± 1.04	46.7 ± 5.34	6.16 ± 0.43	1420 ± 140.53
S.Em ±		1.28	0.33	1.17	0.12	32.81
CD (p=0.05)		3.80	0.99	3.47	0.37	97.49
Interaction (MxS)						
S.Em ±		2.22	0.57	2.02	0.21	56.83
CD (p=0.05)		NS	NS	NS	NS	NS

Table 4: Quality parameters of Bt cotton as influenced by different levels of conventional and nano fertilizers, Kharif 2023

Treatments		Seed index (g)	Lint index (g)	Ginning percentage (%)	Fiber length (mm)	Fiber strength (g tex^{-1})	Fiber fineness (Micronaire)	Uniformity ratio
Main plot: Conventional fertilizer (M): 03								
M_1	50 % of recommended N and P kg ha^{-1}	11.29 ± 1.16	5.0 ± 1.25	32.88 ± 5.57	33.36 ± 0.53	34.03 ± 1.22	2.72 ± 0.16	85.08 ± 0.58
M_2	75 % of recommended N and P kg ha^{-1}	11.98 ± 1.33	5.82 ± 0.36	34.84 ± 2.36	33.53 ± 3.72	34.67 ± 2.97	2.73 ± 0.11	85.67 ± 4.17
M_3	100 % of recommended N and P kg ha^{-1}	12.04 ± 2.17	7.10 ± 1.87	36.75 ± 5.41	34.55 ± 1.2	35.08 ± 1.57	2.74 ± 0.12	86.33 ± 3.06
S.Em ±		0.12	0.13	0.51	0.26	0.26	0.01	0.33
CD (p=0.05)		0.48	0.53	2.02	NS	NS	NS	NS
Sub plot: Spraying of Nano fertilizer (S): 04								
S_1	Nano urea at 2 ml L^{-1} @ 40, 60 and 80 DAS	10.94 ± 0.38	5.08 ± 0.45	33.09 ± 0.92	33.31 ± 0.61	33.86 ± 1.18	2.68 ± 0.06	85.00 ± 1.46
S_2	Nano urea at 4 ml L^{-1} @ 40, 60 and 80 DAS	11.86 ± 0.51	5.73 ± 1.13	34.38 ± 2.27	33.53 ± 0.57	34.09 ± 0.35	2.69 ± 0.09	85.22 ± 1.68
S_3	Nano DAP at 2 ml L^{-1} @ 40, 60 and 80 DAS	12.06 ± 0.43	6.01 ± 0.81	34.75 ± 3.27	33.92 ± 0.48	35.08 ± 0.37	2.76 ± 0.06	86.11 ± 1.02
S_4	Nano DAP at 4 ml L^{-1} @ 40, 60 and 80 DAS	12.22 ± 0.39	7.46 ± 1.36	37.07 ± 1.77	34.50 ± 1.81	35.33 ± 1.34	2.79 ± 0.02	86.44 ± 1.27
S.Em ±		0.19	0.19	0.84	0.37	0.49	0.04	0.55
CD (p=0.05)		0.56	0.55	2.51	NS	NS	NS	NS
Interaction (MxS)								
S.Em ±		0.33	0.32	1.46	0.65	0.84	0.07	0.96
CD (p=0.05)		NS	NS	NS	NS	NS	NS	NS

Table 5: Economics of Bt cotton as influenced by different levels of conventional and nano fertilizers, Kharif 2023

Treatments		Cost of cultivation (Rs. ha^{-1})	Gross returns (Rs. ha^{-1})	Net returns (Rs. ha^{-1})	B:C ratio
Main plot: Conventional fertilizer (M): 03					
M_1	50 % of recommended N and P kg ha^{-1}	77809	101504	29666	1.38
M_2	75 % of recommended N and P kg ha^{-1}	80692	111789	37673	1.47
M_3	100 % of recommended N and P kg ha^{-1}	83706	123491	47049	1.56
Sub plot: Spraying of Nano fertilizer (S): 04					
S_1	Nano urea at 2 ml L^{-1} @ 40, 60 and 80 DAS	77839	104663	32981	1.42
S_2	Nano urea at 4 ml L^{-1} @ 40, 60 and 80 DAS	79607	110075	36943	1.46
S_3	Nano DAP at 2 ml L^{-1} @ 40, 60 and 80 DAS	80735	113598	39545	1.49
S_4	Nano DAP at 4 ml L^{-1} @ 40, 60 and 80 DAS	84761	120709	43049	1.51

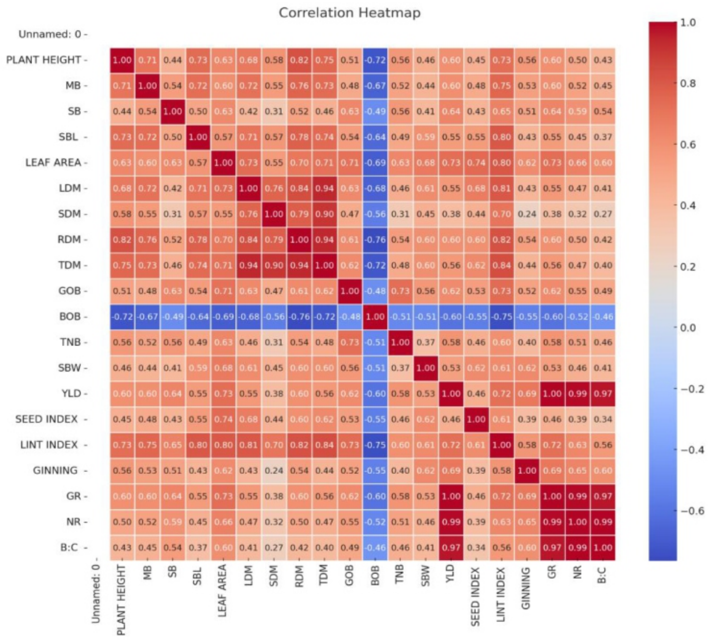

Fig. 1 Correlation analysis among growth, yield, quality and economic traits
MB: Monopodial branches BOB: Bad opened bolls
SB: Sympodial branches TNB: Total number of bolls
SBL: Sympodial branches length SBW: Single boll weight
LDM: Leaf dry matter YLD: Yield
SDM: Stem dry matter GR: Gross returns
RDM: Reproductive dry matter NR: Net returns
TDM: Total dry matter
GOB: Good opened bolls

Conclusion

The present study clearly demonstrates that integrated nutrient management, combining conventional and nano fertilizers, plays a crucial role in enhancing the growth, yield, quality, and economic viability of *Bt* cotton. Among the treatments evaluated, the application of 100 % recommended dose of nitrogen and phosphorus (RDNP) along with foliar spray of nano DAP at 4 ml L^{-1} at 40, 60, and 80 days after sowing proved to be the most effective. This combination significantly improved growth attributes such as plant height, branch development, leaf area, and dry matter accumulation, which collectively supported better reproductive growth. Yield parameters, including total number of bolls, boll weight, and seed cotton yield, showed marked improvements, while quality traits such as seed index, lint index, and ginning percentage also recorded higher values. The enhanced nutrient uptake facilitated by nano DAP not only promoted physiological and metabolic processes but also improved stress tolerance during critical growth stages. Furthermore, the treatment resulted in the highest economic benefits, with increased gross and net returns as well as an improved benefit-cost (B:C) ratio, indicating its feasibility for sustainable cotton production. These findings highlight the potential of integrating nano fertilizers with conventional practices to improve nutrient efficiency, enhance productivity, and support economically viable cotton cultivation under prevailing agro-climatic conditions.

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Author Contribution Statement

Sajjan G. – Lead conceptualization; Project administration; Data curation; Formal analysis; Investigation; Writing – original draft; Supervision.
Shashi Kumar C. – Conceptualization; Methodology development; Writing – review & editing; Validation; Investigation; Supervision.
Pravalika K. M., Hemanth D. – Data curation; Investigation; Methodology support.
Gaurav Vinod Rao Sadafale – Review & editing.

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Conflict Of Interest

The authors declare that they have no financial or non-financial conflict of interest.

Data Availability

Data will be available on request.

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