



Effect of Nano-fertilizers on Growth and Yield Performance of Cauliflower (*Brassica oleracea* var. *botrytis* L.)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The study aimed to assess the influence of different nutrient regimes involving conventional and nano NPK fertilizers on key growth and yield parameters of cauliflower, including plant height, number of leaves per plant, leaf area, days to curd initiation, polar and equatorial curd diameters, gross and net curd weights, and overall yield. Conducted from September 2022 to March 2023 at the Experimental Farm of the Department of Soil Science and Water Management, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (Himachal Pradesh), the experiment followed a Randomized Block Design (RBD) comprising 11 treatment combinations, each replicated three times. The treatments included various combinations of recommended doses of conventional fertilizers (RDF) and foliar applications of nano-NPK fertilizers at concentrations of 0.25%, 0.5%, and 1.0%. The cauliflower cultivar used was Pusa Snowball K-1. Observations were recorded on vegetative growth parameters (plant height, number of leaves, leaf area), physiological

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traits (days to curd initiation), curd development parameters (polar and equatorial diameters), and yield components (gross and net curd weights, and total yield per plot and per hectare). Results revealed that the integrated application of 1.0% nano-NPK with 80% RDF (Treatment T7) significantly outperformed all other treatments, recording the highest values in all measured parameters: plant height (51.39 cm), number of leaves per plant (21.03), leaf area (1126.00 cm²), earliest curd initiation (88.91 days), curd diameters (13.50 cm and 15.06 cm), gross curd weight (1341.81 g), net curd weight (809.56 g), and yield (293.12 q ha⁻¹). In contrast, the absolute control (T11) consistently showed the lowest performance. The findings demonstrate that integrating nano-NPK with reduced levels of conventional fertilizers is an effective and sustainable nutrient management strategy for improving growth, curd development, and productivity in cauliflower, while enhancing nutrient-use efficiency and supporting environmentally sound agricultural practices.

Keywords: *Cauliflower; nano-fertilizers; conventional fertilizers; growth parameters; curd development; sustainable vegetable production.*

1. INTRODUCTION

The increasing global demand for food amidst shrinking natural resources has posed a significant challenge to modern agriculture. Sustainable farming practices that enhance productivity while preserving environmental health have become imperative (Pretty and Bharucha, 2014). In India, where vegetables are an essential component of the daily diet, improving the efficiency of vegetable production is not only vital for food security but also crucial for rural livelihoods and nutritional enhancement (Karlund et al., 2024). Among vegetables, cauliflower (*Brassica oleracea* var. *botrytis*) is a highly valued crop grown extensively across India. It is an excellent source of essential nutrients, including vitamins C, A, K, and B-complex, along with minerals like calcium, magnesium, potassium, and iron (Karthika et al., 2020). Due to its high nutritional content and wide consumer preference, cauliflower has become a key crop in diversified farming systems, especially in states like Himachal Pradesh, where favorable agro-climatic conditions support year-round vegetable cultivation.

Despite advances in crop management, the actual yield of cauliflower remains below its potential due to various agronomic limitations, particularly low nutrient use efficiency. Conventional fertilization practices, while effective in enhancing productivity, are plagued by issues such as nutrient leaching, volatilization, and low absorption efficiency, often resulting in reduced soil health, environmental pollution, and economic inefficiency (Kumar et al., 2020; Panhwar et al., 2019). The nutrient use efficiency of nitrogen (N), phosphorus (P), and potassium (K) in conventional systems is estimated to be

only 30–50%, contributing to both production losses and environmental concerns (Bihari et al., 2022).

In recent years, nanotechnology has emerged as a promising tool for addressing these challenges. Nano-fertilizers, owing to their extremely small particle size and high surface area, improve nutrient delivery and uptake efficiency, thereby reducing environmental nutrient losses. Their controlled release and targeted delivery allow for sustained nutrient availability during critical growth phases, which in turn can lead to improved vegetative development, early reproductive growth, and higher crop yields (Solanki et al., 2015; Jakhar et al., 2022). When used in conjunction with recommended doses of conventional fertilizers (RDF), nano-fertilizers have shown synergistic effects in improving various plant growth and yield traits.

For a crop like cauliflower, parameters such as plant height, number of leaves per plant, and leaf area are essential indicators of vegetative vigor and are directly influenced by nutrient availability and uptake. Enhanced leaf area and foliage density contribute to increased photosynthetic efficiency, supporting better biomass accumulation and curd development. Timely curd initiation, another key physiological milestone, ensures the transition from vegetative to reproductive stages under optimal environmental and nutritional conditions. Furthermore, curd size attributes like Polar (longitudinal) and equatorial (transverse) diameters, along with gross and net curd weight serve as vital economic traits influencing marketability and profitability.

In this context, nano-fertilizers, when applied via foliar routes, can support rapid and effective nutrient assimilation through leaf stomata,

enhancing these morphological and physiological parameters (Saurabh et al., 2024). Improved nutrient dynamics under nano-fertilizer regimes may therefore contribute not only to better curd formation and yield but also to shortened crop cycles, enabling efficient land use. Given the current need for sustainable intensification of vegetable production systems, the present study was undertaken to evaluate the effect of combined application of nano-NPK and conventional fertilizers on the growth and yield parameters of cauliflower. Specifically, the study focused on quantifying improvements in plant height, leaf count, leaf area, curd initiation timing, curd dimensions, and curd weights. By assessing these indicators under varying treatment combinations, the research aims to provide insights into optimizing nutrient strategies for enhanced productivity, economic returns, and environmental sustainability in cauliflower cultivation.

2. MATERIALS AND METHODS

2.1 Experimental Site and Climate

The field investigation was conducted during September 2022 to March 2023 at the Experimental Farm of the Department of Soil Science and Water Management, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh. The site falls under the Zone II (sub-temperate, sub-humid) agro-climatic zone of Himachal Pradesh. The region experiences an average annual rainfall of approximately 1150 mm, with most precipitation occurring during the monsoon season (June-September). The soil at the experimental site was sandy clay loam in texture, and nearly neutral pH (6.68).

2.2 Experimental Design and Treatments

The experiment was laid out in a Randomized Block Design (RBD) with 11 treatments and three replications. The treatment combinations included varying levels of conventional fertilizers (RDF) and foliar-applied nano-NPK fertilizers. Conventional nutrients were applied using urea (46% N), single super phosphate (16% P₂O₅), and muriate of potash (60% K₂O), while nano-fertilizers included nano urea, divanophos (nano-P), and nano K (Geolife). Nano-NPK was applied as a foliar spray at 30 and 60 days after transplanting at concentrations of 0.25%, 0.5%, and 1.0%. Each treatment was calculated based on the plot size of 2.1 m × 2.1 m.

The cauliflower cultivar used was Pusa Snowball K-1 (PSBK-1). Healthy, uniform one-month-old seedlings of cauliflower were transplanted at a spacing of 60 × 45 cm, accommodating 21 plants per plot. Standard agronomic practices were followed throughout the cropping period.

2.3 Plant Growth and Yield Parameters

Observations were recorded from five randomly selected and tagged plants per plot for each of the following parameters:

Plant Height (cm): Measured from the ground surface to the tip of the tallest leaf at harvest using a measuring scale.

Number of Leaves per Plant: Counted manually at curd maturity from each selected plant, and the average was calculated.

Leaf Area (cm²): Calculated by multiplying the average length and width of the largest leaves at the time of curd maturity.

Days to Curd Initiation: Number of days taken from transplanting to visible curd formation was recorded and averaged for each treatment.

Curd Diameter (cm): Both polar (longitudinal) and equatorial (transverse) diameters were measured using a vernier caliper after cutting the curd appropriately.

Gross Curd Weight (g): Total weight of the harvested curd including non-marketable outer leaves and stalk, recorded using a digital balance.

Net Curd Weight (g): Weight of the marketable curd only (excluding leaves and stalk) at maturity.

2.4 Statistical Analysis

The recorded data were statistically analyzed using analysis of variance (ANOVA) at a 5% level of significance, following the procedure outlined by Panse and Sukhatme (2000). Mean comparisons were carried out using the OPSTAT statistical package, and treatment means were separated using CD (Critical Difference) at 0.05 probability level.

3. RESULTS

The data recorded during the study indicated significant differences among the treatments for plant growth and yield attributes of cauliflower.

3.1 Plant Growth Parameters

The application of different combinations of conventional and nano-fertilizers had a significant impact on plant growth attributes of cauliflower. Among all treatments, the tallest plants were recorded in T7, which attained a height of 51.39 cm, indicating vigorous vegetative growth under this nutrient regime (Fig. 1). This was closely followed by T4 (50.94 cm) and T8 (50.72 cm). On the contrary, the shortest plants were observed in the unfertilized control treatment T11 (35.35 cm), which clearly highlights the importance of balanced and efficient nutrient management in enhancing plant stature.

The number of leaves per plant, a crucial vegetative parameter, also varied significantly across treatments as shown in Fig. 2. The maximum number of leaves was observed in T7 (21.03), which was statistically comparable to T4 (20.13) and T8 (19.17). These treatments demonstrated a substantial improvement in leaf production, possibly due to better nutrient uptake and assimilation through nano-fertilizers. In contrast, the minimum number of leaves was observed in T11 (14.08), further validating the critical role of nutrient inputs in supporting robust foliage development.

Leaf area, which directly correlates with the photosynthetic capacity of the plant, was significantly influenced by the treatment combinations as presented in Fig. 3. The largest leaf area was recorded in T7 (1126.00 cm²), followed closely by T4 (1123.70 cm²) and T8 (1102.33 cm²). These treatments led to the development of larger canopy structures, which

are essential for effective light interception and photosynthesis. Conversely, T11 had the smallest leaf area (991.67 cm²), reflecting a restricted vegetative growth likely due to nutrient inadequacy.

3.2 Curd Initiation and Development

The number of days taken for curd initiation was significantly affected by nutrient treatments (Fig. 4). The earliest curd formation was observed in T7 (88.91 days), followed closely by T4 (89.62 days) and T8 (90.61 days). These early curd initiation responses under nano-fertilizer-based treatments indicate enhanced physiological efficiency and faster developmental progression in the crop. In comparison, the control treatment T11 showed the most delayed curd initiation (104.72 days), emphasizing the retardation of developmental stages under nutrient-limited conditions.

The curd size, measured in terms of polar and equatorial diameters, also exhibited significant improvements in response to fertilizer treatments (Fig. 5). The largest polar curd diameter was recorded in T7 (13.50 cm), followed by T4 (13.26 cm) and T8 (12.79 cm). Similarly, the equatorial diameter was also highest under T7 (15.06 cm), with T4 (14.96 cm) and T8 (14.79 cm) showing comparable results. These increases in curd dimensions are indicative of enhanced cellular expansion and curd compactness under nano-fertilizer treatments. The smallest polar and equatorial diameters were recorded in T11 (6.70 cm and 9.04 cm, respectively), again illustrating the detrimental effect of nutrient deficiency on curd development.

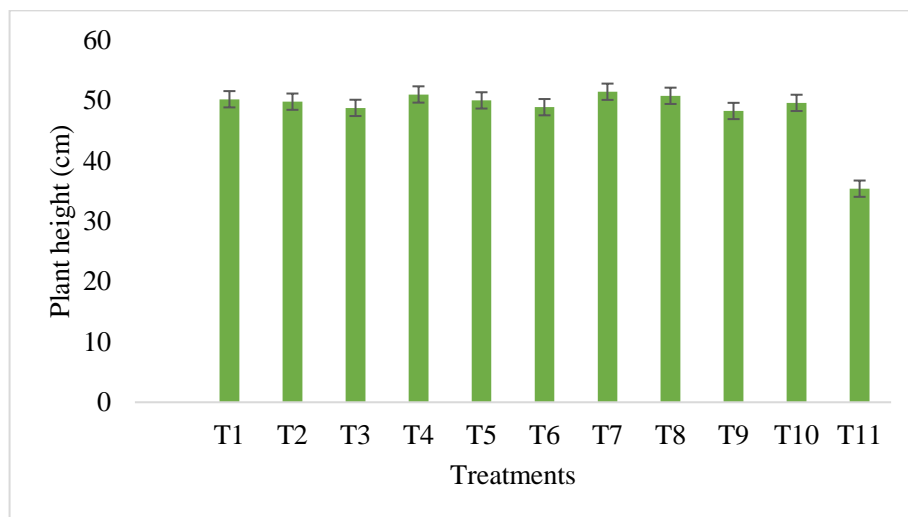


Fig. 1. Influence of various nutrient treatments on plant height of cauliflower

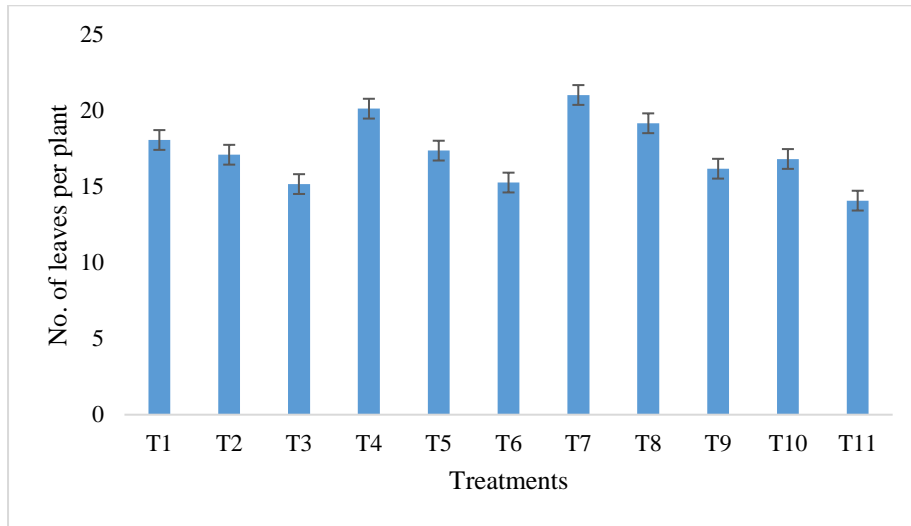


Fig. 2. Influence of various nutrient treatments on number of leaves per plant

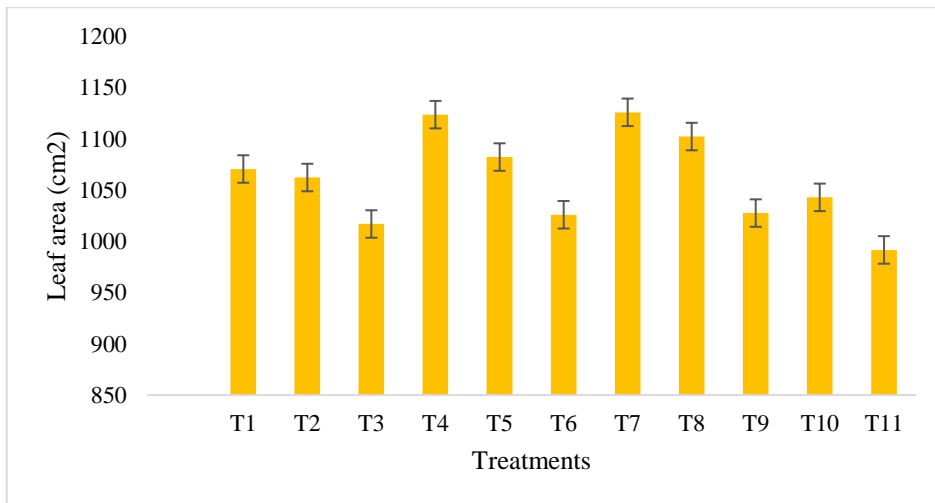


Fig. 3. Influence of various nutrient treatments on leaf area of cauliflower

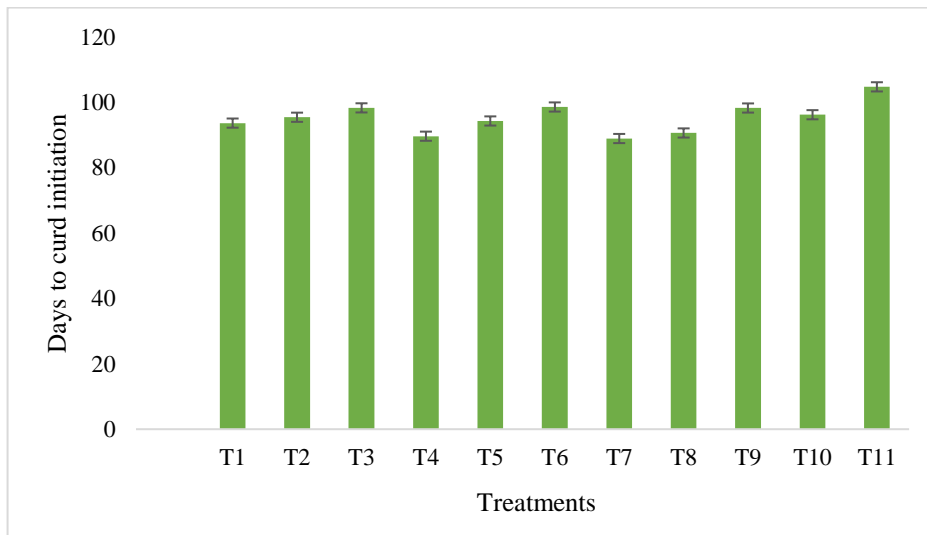


Fig. 4. Influence of various nutrient treatments on days to curd initiation of cauliflower

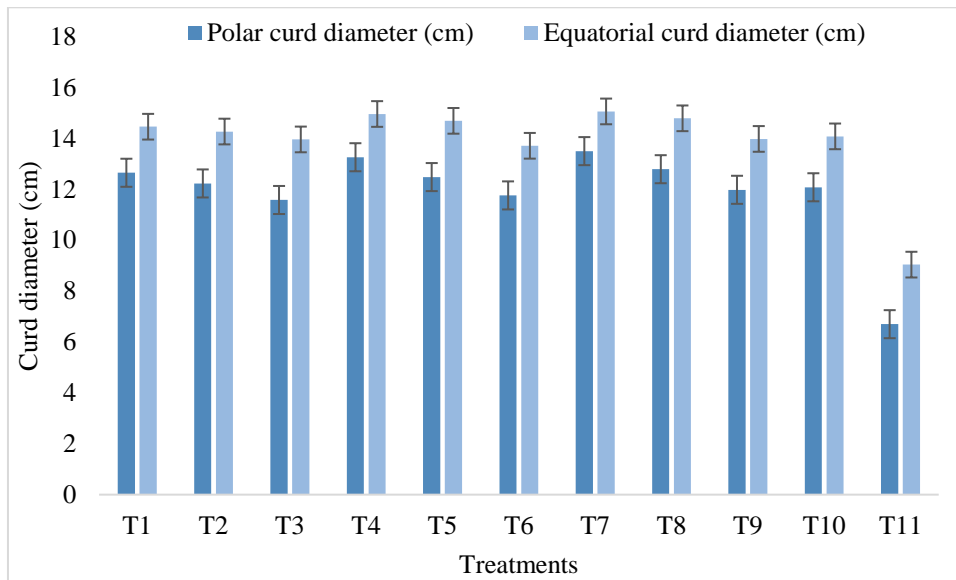


Fig. 5. Influence of various nutrient treatments on curd diameter of cauliflower

3.3 Curd Weight and Yield

Both gross and net curd weights demonstrated significant enhancement due to fertilizer application (Fig. 6). Treatment T7 resulted in the highest gross curd weight (1341.81 g) and net curd weight (809.56 g), closely followed by T4 (1325.85 g gross, 791.81 g net) and T8 (1287.48 g gross, 776.55 g net). These results confirm that the integration of nano-fertilizers led to increased biomass accumulation and better curd filling. On the other hand, the lowest gross and net weights were observed under control T11 (960.91 g and 453.43 g, respectively), underscoring the poor

curd development in the absence of nutrient supplementation.

3.4 Yield

The yield of cauliflower was significantly influenced by different nutrient treatment combinations (Fig. 7). The maximum yield was recorded in T7 (291.28 q ha⁻¹), which was statistically at par with T4 (280.76 q ha⁻¹) and T8 (276.70 q ha⁻¹). In contrast, the lowest yield was observed in the control treatment T11 (167.14 q ha⁻¹), reflecting the adverse effects of nutrient deficiency on crop productivity.

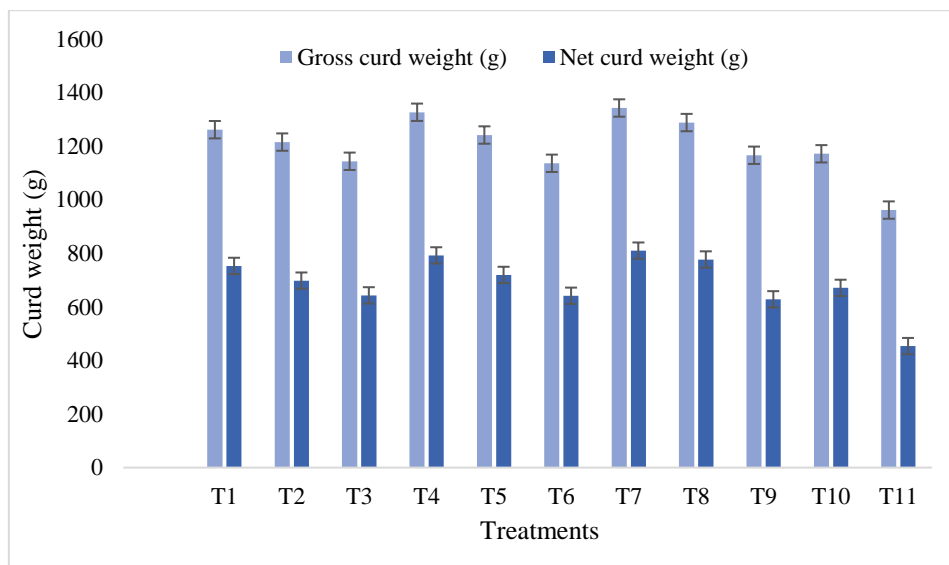


Fig. 6. Influence of various nutrient treatments on curd weight of cauliflower

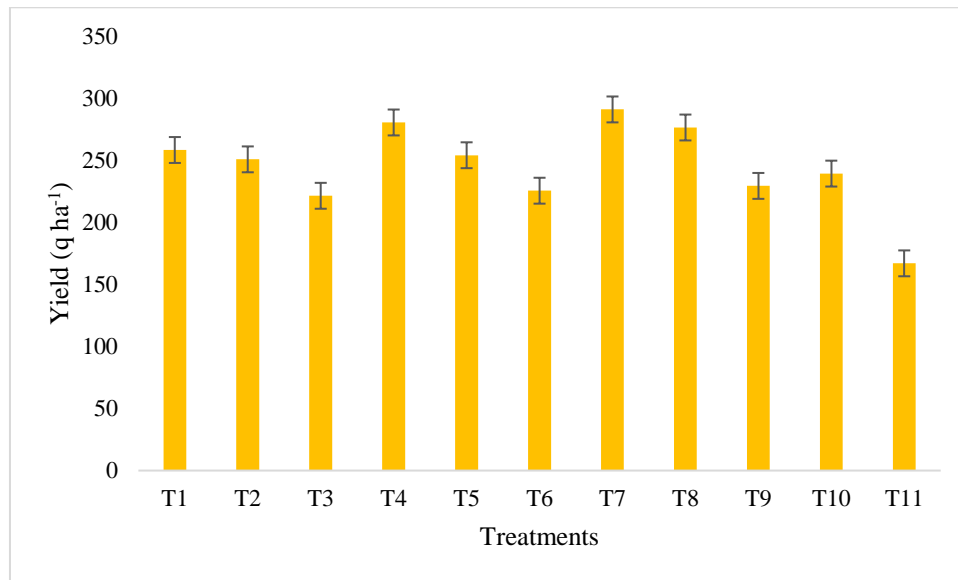


Fig. 7. Influence of various nutrient treatments on yield of cauliflower

The results from the study clearly indicate that the application of nano-fertilizers, particularly in treatment T7, significantly improved all growth and yield parameters of cauliflower. This treatment consistently outperformed others across plant height, leaf area, curd initiation, curd size, curd weight, and total yield. The study highlights the potential of nano-fertilizers in improving nutrient efficiency and productivity, thereby offering a sustainable alternative to conventional fertilization practices.

4. DISCUSSION

The present study clearly demonstrates that the integrated application of nano-NPK fertilizers along with the recommended dose of conventional fertilizers (RDF) significantly enhances the growth, physiological efficiency, yield, and quality parameters of cauliflower. These improvements are largely attributed to the unique properties of nano-fertilizers, particularly their high surface area, greater solubility, and targeted nutrient delivery mechanisms.

One of the most notable vegetative responses observed in the current study was the significant increase in the number of leaves per plant under nano-NPK treatments, especially when combined with RDF. This enhancement can be primarily attributed to the increased availability and efficient uptake of nitrogen (N), a key macronutrient responsible for chlorophyll synthesis, protein formation, and vigorous vegetative growth. As supported by Amanullah et

al. (2014), nitrogen promotes chlorophyll content and photosynthetic efficiency, which in turn enhances cell division and leaf proliferation (Singh et al., 2024). The foliar application of nano-NPK ensures a sustained and continuous nutrient supply during the early vegetative stages (Abdel-Aziz et al., 2016), leading to a denser and more efficient canopy structure (Panda et al., 2020). This trend is supported by various studies (e.g. El-Henawy et al., 2018; Abdelkader et al., 2024 and Rahman et al., 2021b), who also reported a significant increase in leaf number in response to nano-fertilizer application.

The reduction in the number of days required for curd initiation observed in the study under nano-NPK treatments is another significant outcome. This early initiation is likely the result of precise and timely delivery of critical nutrients, particularly phosphorus (P) and potassium (K). Phosphorus is involved in energy transfer and root development, while potassium plays a role in enzyme activation and water regulation. Together, they promote faster physiological and reproductive transitions, leading to early curd development (Amanullah et al., 2014; Abdel-Aziz et al., 2016). The findings align with those of Pooja et al. (2022) and Salman and Razzaq (2022), who reported similar outcomes in broccoli with the application of nano-fertilizers.

Cauliflower curd size, evaluated through polar and equatorial diameters, showed a marked improvement under nano-NPK treatments. The controlled release and high nutrient-use

efficiency provided by nano-NPK ensures a sustained supply of essential nutrients during the curd development phase. Nitrogen supports vegetative growth and photosynthate production, while potassium maintains turgor pressure and regulates stomatal function, enabling cell expansion and curd enlargement. Phosphorus, in turn, enhances metabolic energy transfer, contributing to rapid tissue differentiation and curd growth (Tarafdar et al., 2014; Upadhyaya et al., 2017; Sohair et al., 2018). These mechanisms culminate in larger, more compact, and market-preferred curds. The results of this study corroborate earlier findings by Ibraheem et al. (2021), Durgude et al. (2022), Pooja et al. (2022), and Kumar et al. (2023), who observed similar improvements in curd dimensions in response to nano-fertilizer application.

The application of nano-NPK in combination with RDF also led to a significant increase in both gross and net curd weight, a crucial determinant of cauliflower yield and market value. This improvement stems from improved nutrient absorption, translocation, and assimilation resulting from the nano-formulation's ability to penetrate plant tissues efficiently—especially via stomata and cuticular pathways. The quick absorption and systemic movement of nutrients ensures that photosynthates are preferentially directed toward curd development, enhancing both structural and biochemical components (Elemike et al., 2019; Kumar et al., 2020). The synergistic effects of N, P, and K support higher metabolic activity, which may contribute to denser and heavier curds. Similar observations were reported in studies on cauliflower and broccoli by Pooja et al. (2022), Salman and Razzaq (2022), and Kumar et al. (2023).

The most impactful outcome of nano-NPK and RDF integration was the significant improvement in total cauliflower yield per plot and per hectare. The increase in yield can be linked to several factors: enhanced nutrient-use efficiency, improved root architecture, and better nutrient partitioning towards economically important sink tissues (Verma et al., 2022). Nano-fertilizers facilitate slow and controlled nutrient release, preventing leaching and volatilization losses, and ensuring a steady nutrient supply throughout the crop's lifecycle (Tarafdar et al., 2014; Subramanian and Thirunavukkarasu, 2017). The consistent nutrient availability supports optimal vegetative and reproductive growth, ultimately leading to higher marketable yields. These findings are in close agreement with those of

Mariush and Al-Mharib (2020), and Javed et al. (2022), all of whom reported significant increases in yield with nano-fertilizer applications across various crops. Collectively, the results emphasize that the conjunctive use of nano-NPK with conventional RDF is a superior strategy for enhancing cauliflower growth, curd development, and yield. The nano-fertilizer technology not only improves nutrient delivery and efficiency but also aligns with sustainable agricultural practices by minimizing nutrient losses and maximizing productivity. The consistency of these findings with prior research across crops further validates the potential of nano-fertilizers in modern horticulture.

5. CONCLUSION

Integrated nano-NPK application with reduced conventional fertilizers improved cauliflower growth and yield. Treatment T7 (80% RDF + 1.0% nano-NPK) consistently outperformed all others in terms of plant height, leaf development, early curd initiation, curd size, and yield. The enhanced nutrient-use efficiency and targeted nutrient delivery of nano-fertilizers contributed to better physiological and developmental outcomes. These findings support the adoption of nano-fertilizer technology as a sustainable approach to maximize productivity while minimizing environmental impact. Integrating nano-fertilizers into standard nutrient management may contribute to improved cauliflower cultivation under similar agro-climatic conditions.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

The author(s) hereby declare that no generative AI technologies such as large language models (e.g., ChatGPT, Copilot) or text-to-image generators were used in the writing, editing, or preparation of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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