#### Original Research Article

#### Effect of Nanochitosan and Biocapsule on Growth, yield and Quality of Cabbage cv. Golden Acre

#### Abstract

Nanochitosan, derived from chitosan, a biopolymer found in the exoskeleton of crustaceans has gained attention for its exceptional properties such as biodegradability, biocompatibility and broad-spectrum antimicrobial activity. Nutritionally, cabbage is a powerhouse of essential vitamins and minerals. Cabbage contains heat-sensitive compounds with antibacterial and anti-peptic ulcer effects, further enhancing its nutritional and therapeutic significance. The present investigation was undertaken to evaluate the effect of nanochitosan and biocapsule applications on the growth, yield and quality of cabbage (cv. Golden Acre) under field conditions. The experiment was laid out in a Randomized Block Design (RBD) comprising 15 treatment combinations involving different concentrations of nanochitosan (50, 100 and 150 ppm) and biocapsules (450, 500 and 550 ppm), along with control and was replicated in three times. The study was conducted at the Department of Horticulture, Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj, Uttar Pradesh, during the rabi season of 2024-2025. The results revealed significant differences among the treatments for all growth, yield and quality parameters. The treatment T15: Nanochitosan 150 ppm & Biocapsule 550 ppm recorded the best performance with the highest plant height (33.70 cm), number of leaves per plant (28.45), plant spread (47.88 cm), polar diameter (17.97 cm), equatorial diameter (28.00 cm), gross head weight (1,955.26 g), net head weight (1,410.58 g) and head yield per plot (2.13 kg). The same treatment also showed the earliest maturity (65.76 days) and maximum quality enhancement in terms of total soluble solids (10.08 °Brix) and vitamin C content (38.82 mg/100g). The significant improvement observed with nanochitosan and biocapsule combinations can be attributed to the synergistic effects of enhanced nutrient uptake, improved physiological activity, and the bio-stimulatory impact of beneficial microbes. The findings highlight the potential of integrating nano-based biostimulants and microbial inoculants as a sustainable and effective approach to improving cabbage productivity and nutritional quality. The integration of nanochitosan and biocapsules represents a promising, eco-friendly, and economically viable strategy for sustainable cabbage production. Further research can focus on assessing the long-term environmental impact and scalability of this technology for commercial cultivation.

**Keywords:** nanochitosan, biocapsules, cabbage, growth, yield, quality, biostimulants

#### Introduction

Agriculture lands have low fertilizer retention owing to porosity and irrigation, whereas a significant portion of fertilizer is lost through denitrification, volatilization, surface run-off, and leaching, causing losses of nutrients to air and ground/surface water. Urea fertilizer readily enhances the agricultural yield but also deteriorates the quality of fertile soils. Nanochitosan bring a considerable evaluation in the agriculture sector, such application as a plant growth promoter, disease control, vegetables, fruits coating, etc (Ma et al., 2023). Cabbage (Brassica oleracea var. capitata), a prominent member of the Cruciferae (Brassicaceae) family with a chromosome number of 2n: 18, is a globally cultivated cole crop known for its versatility and nutritional value. Believed to have originated in Western Europe and the Mediterranean region, cabbage is a domesticated form of wild cabbage (B. oleracea var. oleracea, syn. sylvestris), commonly referred to as “Colewart” through natural mutation, introgression, and human selection (Rana *et al.,* 2020). The term “cabbage” derives from the French word Coboche, meaning “head”, referencing the compact leafy head typical of the crop. It grows well across temperate, subtropical, and tropical climates, although optimal yield is achieved in cooler conditions with temperatures ranging between 13°C and 16°C, along with fertile soils and adequate irrigation (Fageria *et al.,* 2003). Apart from being consumed in salads, cooked dishes, and pickles, cabbage has medicinal applications, including the treatment of cough, fever, and skin conditions (Katyal & Chadha, 1985).

Nutritionally, cabbage is a powerhouse of essential vitamins and minerals. Every 100 g of its edible portion provides approximately 2000 IU of vitamin A, 124 mg of vitamin C, 114 mg of potassium, 44 mg of phosphorus, and 39 mg of calcium (Hasan *et al.,* 2018). It also contains sulphur-rich glycosides such as sinigrin, known for imparting its distinct flavour and for possessing anti-carcinogenic properties (Kim *et al.,* 2004; Rai *et al.,* 2005). In addition to these, cabbage contains heat-sensitive compounds with antibacterial and anti-peptic ulcer effects, further enhancing its nutritional and therapeutic significance. India is among the world’s leading cabbage producers, with a total output of 9.1 million metric tonnes from 399,000 hectares and an average productivity of 22.1 tonnes/ha (NHB, 2020). Key contributing states include Uttar Pradesh, Bihar, Odisha, West Bengal, and Maharashtra. In Madhya Pradesh alone, cabbage production stands at 614.44 thousand tonnes from 29,000 hectares.

To address the growing need for sustainable agriculture, innovative inputs such as nanochitosan and biocapsules have emerged as eco-friendly alternatives to traditional agrochemicals. Nanochitosan, derived from chitosan, a biopolymer found in the exoskeleton of crustaceans has gained attention for its exceptional properties such as biodegradability, biocompatibility and broad-spectrum antimicrobial activity (Shahrajabian *et al.,* 2021). When converted to nanoparticles, chitosan exhibits improved solubility and reactivity, making it an ideal carrier for the slow and targeted release of nutrients. These nanofertilizers facilitate enhanced nutrient uptake, stimulate photosynthesis, increase leaf surface area and protect plants from fungal pathogens due to their dual nutrient delivery and antimicrobial action (Wani *et al.,* 2021; Sharma *et al.,* 2024). However, due consideration must be given to their environmental persistence and potential toxicological impacts (Hamed *et al.,* 2024). Nano chitosan has broad antimicrobial activity against fungal pathogens however, the bulk size limits its solubility which affects the antimicrobial property. Chitosan nanoparticles have great potential over the bulk counter parts as size can alter several properties compare to bulk material. The exclusive properties of these materials, such as a large surface area and greater reactivity, have also raised concerns about adverse effects on environmental health (Devi et al., 2022).

Complementing nanochitosan, biocapsules are gelatin-based carriers that encapsulate beneficial microbial strains such as nitrogen-fixers and phosphate-solubilizers. Developed by the Indian Council of Agricultural Research (ICAR), these capsules are highly concentrated and viable, equivalent to traditional bulk biofertilizers in microbial density but superior in shelf life and field efficacy (ICAR, 2022; Dawud *et al.,* 2025). Upon application, the dormant microbes are activated in the soil, where they aid nutrient solubilisation, improve root colonization, and stimulate phytohormone production (Wang *et al.,* 2024). The integration of nanochitosan with biocapsules is expected to produce a synergistic effect, improving nutrient efficiency, boosting plant immunity, and enhancing overall crop performance. Therefore, the present investigation was conducted to evaluate the effect of nanochitosan and biocapsule treatments on the growth, yield, and quality of cabbage (cv. Golden Acre), with specific objectives to identify the best treatment combinations, assess crop performance, and analyse the cost-effectiveness of different treatments under field conditions.

#### Materials and methods

A field experiment was conducted during the rabi season of 2024-2025 at the Horticulture Research Farm, Department of Horticulture, Naini Agricultural Institute, Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj, Uttar Pradesh. The soil of the field was well-drained and standard agronomic practices were followed throughout the cropping period. The experiment was laid out in a randomized block design (RBD) with 16 treatment combinations, each replicated thrice. Treatments included various concentrations of nanochitosan (50, 100, and 150 ppm) and biocapsule (450, 500, and 550 ppm), applied both individually and in combination, along with a control. The soil at the experimental site was **sandy loam** in texture, with a pH of **6.75**, low **organic carbon (0.41%),** and moderate nutrient levels (**N: 215.53 kg/ha, P: 36.38 kg/ha, K: 214.45 kg/ha).** Each plot measured **2.40 × 1.80 m** and accommodated **24 plants,** spaced at **60 cm × 30 cm. Nanochitosan and biocapsules were applied as soil drenches** immediately after transplanting and at **15-day intervals.** Observations were recorded on growth parameters such as plant height (cm), number of leaves per plant, plant spread (cm) and days to horticultural maturity. Yield parameters included polar and equatorial head diameter (cm), gross and net head weight (g) and head yield per plot (kg), which was extrapolated to yield per hectare (t/ha). Quality parameters assessed were total soluble solids (TSS, °Brix) and vitamin C content (mg/100 g fresh weight).

#### Results and Discussion

The present study was conducted to evaluate the effect of nanochitosan and biocapsule treatments on the growth parameters of cabbage cv. Golden Acre. Growth attributes such as plant height, number of leaves per plant, and plant spread were recorded at 20, 40 and 60 days after transplanting (DAP) and significant differences were observed among the treatments, which are represented and illustrated in Table 1 and Figure 1.

#### 1. Effect of nanochitosan and biocapsule on growth parameters in cabbage

The data showed a significant and progressive increase in plant height across all stages (20, 40, and 60 DAP) with the application of nanochitosan and biocapsules. The maximum plant height at 20 DAP (17.85 cm), 40 DAP (28.93 cm) and 60 DAP (33.70 cm) was recorded in treatment **T15: Nanochitosan 150 ppm & Biocapsule 550 ppm**, followed closely by **T14: Nanochitosan 150 ppm & Biocapsule 500 ppm** (17.74, 28.67 and 33.52 cm, respectively). In contrast, the minimum plant height was consistently observed in **T0: Control** (13.27, 20.47 and 26.55 cm). The enhanced plant height in nanochitosan and biocapsule-treated plants can be attributed to improved nutrient uptake and hormone stimulation, particularly gibberellins and auxins, which promote cell division and elongation (Waleed, 2016). This aligns with previous findings by Shahrajabian *et al.* (2021) and Sharma *et al.* (2024), who reported improved vegetative growth with nanochitosan applications.

The number of leaves followed a similar trend to plant height. The highest leaf count at 20 DAP (9.49), 40 DAP (18.44) and 60 DAP (28.45) was also observed in **T15: Nanochitosan 150 ppm & Biocapsule 550 ppm**, followed by **T14: Nanochitosan 150 ppm & Biocapsule 500 ppm**(9.33, 18.37 and 28.39). The lowest number of leaves was recorded in **T0: Control** at all three intervals (6.57, 12.87 and 21.65). The increase in leaf production with combined nanochitosan and biocapsule treatments could be due to enhanced photosynthetic activity and nitrogen assimilation, supported by microbial action in the rhizosphere (Matthews**,2020**). Similar results were reported by Can *et al.* (2022) and Dawud *et al.* (2025), who observed that biocapsules containing plant growth-promoting microbes contribute to increased leaf development through the production of IAA and cytokinin.

Significant differences were observed in plant spread with treatment **T15**: **Nanochitosan 150 ppm & Biocapsule 550 ppm** recording the highest plant spread at 20 DAP (17.97 cm), 40 DAP (39.21 cm) and 60 DAP (47.88 cm), followed by **T14: Nanochitosan 150 ppm & Biocapsule 500 ppm** (17.77, 39.11 and 47.21 cm). The minimum spread was observed in **T0: Control** (13.17, 33.23 and 41.27 cm). The improved plant spread in treated plots is likely the result of enhanced cellular expansion and turgor maintenance due to better nutrient and water absorption, facilitated by nanochitosan’s increased surface area and biocapsule-mediated microbial activity (Wang *et al.,* 2024). These findings indicate that the integrated application of nano-based fertilizers and microbial biocapsules is a promising approach for improving cabbage growth under field conditions in a sustainable and eco-friendly manner (Ali *et al.,* 2023). These results align with findings by Sangwan *et al.* (2023), where an increased plant biomass and leaf expansion in crops treated with chitosan nano-formulations.

**Table 1: Effect of Nanochitosan and Biocapsule for Growth Parameters in cabbage cv. Golden Acre**

|  |  |  |  |
| --- | --- | --- | --- |
| **Treatments** | **Plant height (cm)** | **Number of Leaves** | **Plant spread (cm)** |
| **20 DAP** | **40 DAP** | **60 DAP** | **20 DAP** | **40 DAP** | **60 DAP** | **20 DAP** | **40 DAP** | **60 DAP** |
| T0 : Control | 13.27 | 20.47 | 26.55 | 6.57 | 12.87 | 21.65 | 13.17 | 33.23 | 41.27 |
| T1 : Biocapsule 450 ppm | 14.48 | 22.32 | 27.84 | 7.14 | 13.98 | 23.13 | 14.07 | 34.11 | 42.13 |
| T2 :Biocapsule 500 ppm | 14.91 | 23.05 | 28.37 | 7.46 | 14.98 | 23.98 | 14.57 | 34.81 | 42.91 |
| T3 : Biocapsule 550 ppm | 14.87 | 23.77 | 29.27 | 7.73 | 15.88 | 24.83 | 15.17 | 35.56 | 43.53 |
| T4 : Nanochitosan 50 ppm | 14.99 | 24.53 | 29.49 | 7.87 | 16.32 | 25.35 | 15.57 | 36.01 | 43.98 |
| T5 : Nanochitosan 50 ppm & Biocapsule 450 ppm | 16.3 | 25.78 | 30.77 | 8.33 | 16.84 | 26.18 | 16.07 | 36.76 | 44.78 |
| T6 : Nanochitosan 50 ppm & Biocapsule 500 ppm | 16.48 | 26.37 | 31.18 | 8.52 | 17.18 | 26.83 | 16.43 | 37.11 | 44.87 |
| T7 : Nanochitosan 50 ppm & Biocapsule 550 ppm | 16.81 | 26.91 | 31.75 | 8.73 | 17.52 | 27.48 | 16.87 | 37.51 | 45.48 |
| T8 : Nanochitosan 100 ppm | 15.95 | 25.05 | 30.22 | 8.18 | 16.78 | 26.88 | 16.27 | 36.91 | 44.96 |
| T9 : Nanochitosan 100 ppm & Biocapsule 450 ppm | 16.85 | 27.48 | 32.12 | 8.82 | 17.76 | 27.73 | 17.07 | 38.11 | 46.11 |
| T10 : Nanochitosan 100 ppm & Biocapsule 500 ppm | 17.25 | 27.93 | 32.88 | 9.07 | 18.01 | 28.08 | 17.27 | 38.41 | 46.48 |
| T11 : Nanochitosan 100 ppm & Biocapsule 550 ppm | 17.48 | 28.13 | 33.17 | 9.24 | 18.17 | 28.27 | 17.47 | 38.71 | 46.76 |
| T12 : Nanochitosan 150 ppm | 15.89 | 25.88 | 30.98 | 8.48 | 17.07 | 26.98 | 16.97 | 38.01 | 46.28 |
| T13 : Nanochitosan 150 ppm & Biocapsule 450 ppm | 17.01 | 27.99 | 32.99 | 9.27 | 18.23 | 28.33 | 17.57 | 38.96 | 47.07 |
| T14 : Nanochitosan 150 ppm & Biocapsule 500 ppm | 17.74 | 28.67 | 33.52 | 9.33 | 18.37 | 28.39 | 17.77 | 39.11 | 47.21 |
| T15 : Nanochitosan 150 ppm & Biocapsule 550 ppm | 17.85 | 28.93 | 33.7 | 9.49 | 18.44 | 28.45 | 17.97 | 39.21 | 47.88 |
| **F-Test** | **S** | **S** | **S** | **S** | **S** | **S** | **S** | **S** | **S** |
| **S.Ed (&)** | **0.16** | **0.09** | **0.16** | **0.06** | **0.03** | **0.01** | **0.01** | **0.02** | **0.12** |
| **CD0.05** | **0.34** | **0.18** | **0.33** | **0.12** | **0.07** | **0.03** | **0.02** | **0.04** | **0.25** |
| **CV** | **1.26** | **0.43** | **0.64** | **0.88** | **0.25** | **0.07** | **0.08** | **0.06** | **0.34** |

**Figure 1. Graphical representation on the effect of nanochitosan and biocapsule** **on plant height, number of leaves and plant spread of cabbage cv. Golden Acre at 20, 40 and 60 DAP**

#### 2. Effect of Nanochitosan and Biocapsule for Yield Parameters in cabbage

The effect of nanochitosan and biocapsule applications on cabbage yield attributes such as days to horticultural maturity, polar diameter, equatorial diameter, gross head weight, net head weight and head yield per plot was significant and are represented in Table 2.

The earliest maturity was recorded in **T15: Nanochitosan 150 ppm & Biocapsule 550 ppm**, which achieved maturity in 65.76 days, followed by **T14: Nanochitosan 150 ppm & Biocapsule 500 ppm** (67.08 days). In contrast, the **T0: Control** required the longest time to mature (75.93 days). The reduced days to maturity in higher-dose treatments may be due to the improved physiological efficiency and faster nutrient uptake facilitated by nanochitosan and microbial activity from biocapsules, leading to accelerated developmental processes (Sharma *et al.,* 2024; Hamed *et al.,* 2024).

Cabbage heads under **T15: Nanochitosan 150 ppm & Biocapsule 550 ppm** recorded the largest polar diameter (17.97 cm) and equatorial diameter (28.00 cm), followed by **T14: Nanochitosan 150 ppm & Biocapsule 500 ppm** (17.84 cm and 27.82 cm). The smallest diameters were observed in the **T0: Control** at 13.33 cm (polar) and 22.53 cm (equatorial). The increase in head size can be attributed to the synergistic effect of nanochitosan and beneficial microbes, which enhance cellular expansion and division, contributing to the larger and denser head formation (Kim *et al.,* 2004; Wang *et al.,* 2024).

A significant increase in head weight was observed in treated plants, with **T15: Nanochitosan 150 ppm & Biocapsule 550 ppm** achieving the highest gross head weight (1,955.26 g) and net head weight (1,410.58 g), followed closely by **T14: Nanochitosan 150 ppm & Biocapsule 500 ppm** (1,930.54 g and 1,380.56 g). The lowest values were recorded in **T0: Control** (1,367.57 g gross and 848.21 g net). This improvement in biomass is likely due to improved nutrient-use efficiency and enhanced plant metabolism induced by nanochitosan, combined with the sustained microbial action of biocapsules that enhance soil fertility and plant health (Dawud *et al.,* 2025; Shahrajabian *et al.,* 2021).

The highest head yield was recorded in **T15: Nanochitosan 150 ppm & Biocapsule 550 ppm** (2.13 t/hac), followed by **T14: Nanochitosan 150 ppm & Biocapsule 500 ppm** (2.05 t/ hac). The **T0: Control** yielded the least (1.22 t/ hac) and the variations among the different treatments studied is shown in Figure 3. The progressive increase in yield with higher doses of nanochitosan and biocapsules highlights their combined effectiveness in boosting cabbage productivity. These results affirm the role of nano-biostimulants in optimizing input use, improving plant vigor, and enhancing marketable yield in cabbage production systems (Asgari-Targhi *et al.,* 2018). This supports the hypothesis that integrating nanotechnology with microbial biofertilizers provides a sustainable and high-performing approach to crop nutrition and productivity (Shams, 2019).

**Table 2: Effect of Nanochitosan and Biocapsule for Yield Parameters and Quality Parameters in cabbage cv. Golden Acre**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Treatments** | **Days to Horticultural maturity** | **Polar Diameter (cm)** | **Equatorial Diameter (cm)** | **Gross Head Wt. (g)** | **Net Head Wt. (g)** | **Head Yield/ hectare** **(t/ha)** | **TSS (0Brix)** | **Vit. C****(mg/100g)** |
| T0 : Control | 75.93 | 13.33 | 22.53 | 1,367.57 | 848.213 | 1.22 | 6.36 | 30.19 |
| T1 : Biocapsule 450 ppm | 75.13 | 13.89 | 23.23 | 1,450.70 | 902.387 | 1.28 | 6.83 | 31.5 |
| T2 :Biocapsule 500 ppm | 74.87 | 14.19 | 23.83 | 1,498.26 | 950.567 | 1.35 | 7.18 | 32.14 |
| T3 : Biocapsule 550 ppm | 73.89 | 14.94 | 24.39 | 1,520.08 | 975.187 | 1.39 | 7.43 | 32.88 |
| T4 : Nanochitosan 50 ppm | 74.26 | 15.08 | 25.02 | 1,580.41 | 1,020.43 | 1.45 | 7.68 | 33.32 |
| T5 : Nanochitosan 50 ppm & Biocapsule 450 ppm | 70.87 | 15.63 | 25.39 | 1,625.26 | 1,075.29 | 1.53 | 7.93 | 34.08 |
| T6 : Nanochitosan 50 ppm & Biocapsule 500 ppm | 73.77 | 15.95 | 25.58 | 1,670.81 | 1,120.81 | 1.59 | 8.02 | 34.64 |
| T7 : Nanochitosan 50 ppm & Biocapsule 550 ppm | 72.04 | 16.19 | 26.02 | 1,705.18 | 1,155.88 | 1.64 | 8.43 | 35.14 |
| T8 : Nanochitosan 100 ppm | 71.77 | 16.5 | 26.33 | 1,725.77 | 1,185.35 | 1.68 | 8.68 | 35.76 |
| T9 : Nanochitosan 100 ppm & Biocapsule 450 ppm | 72.96 | 16.79 | 26.6 | 1,750.57 | 1,187.46 | 1.68 | 8.94 | 36.25 |
| T10 : Nanochitosan 100 ppm & Biocapsule 500 ppm | 71.47 | 17.03 | 27.08 | 1,800.36 | 1,265.65 | 1.79 | 9.18 | 36.92 |
| T11 : Nanochitosan 100 ppm & Biocapsule 550 ppm | 69.28 | 17.29 | 27.12 | 1,835.86 | 1,300.36 | 1.84 | 9.37 | 37.16 |
| T12 : Nanochitosan 150 ppm | 68.97 | 17.48 | 27.38 | 1,865.71 | 1,325.87 | 1.88 | 9.58 | 37.49 |
| T13 : Nanochitosan 150 ppm & Biocapsule 450 ppm | 68.15 | 17.65 | 27.63 | 1,900.81 | 1,350.71 | 1.91 | 9.74 | 37.97 |
| T14 : Nanochitosan 150 ppm & Biocapsule 500 ppm | 67.08 | 17.84 | 27.82 | 1,930.54 | 1,380.56 | 2.05 | 9.94 | 38.34 |
| T15 : Nanochitosan 150 ppm & Biocapsule 550 ppm | 65.76 | 17.97 | 28 | 1,955.26 | 1,410.58 | 2.13 | 10.08 | 38.82 |
| **F-Test** | **S** | **S** | **S** | **S** | **S** | **S** | **S** | **S** |
| **S.Ed (&)** | **0.12** | **0.08** | **0.09** | **0.17** | **11.77** | **0.05** | **0.05** | **0.03** |
| **CD0.05** | **0.25** | **0.17** | **0.19** | **0.35** | **24.16** | **0.12** | **0.11** | **0.06** |
| **CV** | **0.2** | **0.63** | **0.43** | **0.01** | **1.25** | **4.39** | **0.83** | **0.1** |

#### 3. Effect of Nanochitosan and Biocapsule for Quality Parameters in cabbage

The impact of nanochitosan and biocapsule applications on the **quality parameters** of cabbage, specifically Total Soluble Solids (TSS, °Brix) and Vitamin C (mg/100g), was found to be significant, with enhanced values observed in treatments involving both inputs compared to the control, which is demonstrated and depicted in Table 2 and Figure 2.

The TSS content increased steadily with higher concentrations of nanochitosan and biocapsule combinations. The highest TSS value (10.08 °Brix) was recorded in **T15: Nanochitosan 150 ppm & Biocapsule 550 ppm**, followed by **T14: Nanochitosan 150 ppm & Biocapsule 500 ppm** (9.94 °Brix). The **T0: Control** treatment showed the lowest TSS (6.36 °Brix). This increase in soluble solids is attributed to improved metabolic activity and photosynthesis efficiency, promoted by nanochitosan's enhanced nutrient delivery and the bioavailability improvements driven by biocapsules (Chadha, 2021). Similar results have been reported by Lalima (2023), suggesting that nanochitosan stimulates sugar synthesis, while biocapsules assist in consistent microbial nutrient release.

The ascorbic acid (Vitamin C) content followed a similar trend, with the maximum concentration observed in **T15: Nanochitosan 150 ppm & Biocapsule 550 ppm** (38.82 mg/100g), followed by **T14: Nanochitosan 150 ppm & Biocapsule 500 ppm** (38.34 mg/100g). The lowest Vitamin C content was recorded in **T0: Control** (30.19 mg/100g). This enhancement in Vitamin C is likely due to improved plant physiological processes, particularly the biosynthesis of antioxidants, which is positively influenced by nanochitosan and beneficial microbial interactions. These findings are in line with previous studies by Reddy *et al. (*2022) and Latiff, 2023, who highlighted the role of nanomaterials and biofertilizers in improving the nutritional quality of vegetables. These improvements validate the synergistic role of nanochitosan and biocapsules in producing nutritionally superior and market-preferred cabbage heads under sustainable cultivation practices.

**Figure 2. Graphical representation on the effect of nanochitosan and biocapsule** **on TSS and Vitamin C** **of cabbage cv. Golden Acre**

#### Conclusion

####  The present investigation clearly demonstrated that the combined application of nanochitosan and biocapsules significantly improved the growth, yield and quality parameters of cabbage cv. Golden Acre under field conditions. Among all treatments, the combination of **Nanochitosan 150 ppm and Biocapsule 550 ppm (T15)** consistently recorded the highest values in plant height, number of leaves, plant spread, head size, head weight, yield per plot and quality attributes such as TSS and vitamin C content. This treatment also led to early maturity, indicating a positive influence on the crop's overall physiological development. The improved performance is attributed to the synergistic effects of nanochitosan's enhanced nutrient delivery and antimicrobial properties, along with the fertilizing action of beneficial microbes in the biocapsules. Therefore, the integration of nanochitosan and biocapsules represents a promising, eco-friendly, and economically viable strategy for sustainable cabbage production. Further research can focus on assessing the long-term environmental impact and scalability of this technology for commercial cultivation.

**Figure 3. Graphical representation on the effect of nanochitosan and biocapsule** **on Head yield per hectare** **of cabbage cv. Golden Acre**

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#### Reference

Ali, M., Cybulska, J., Frąc, M., & Zdunek, A. (2023). Application of polysaccharides for the encapsulation of beneficial microorganisms for agricultural purposes: A review. *International Journal of Biological Macromolecules*, *244*, 125-136.

Asgari-Targhi, G., Iranbakhsh, A., & Ardebili, Z. O. (2018). Potential benefits and phytotoxicity of bulk and nano-chitosan on the growth, morphogenesis, physiology, and micropropagation of *Capsicum annuum*. *Plant Physiology and Biochemistry*, *127*, 393-402.

Can, H., Kal, U., Kayak, N., Dal, Y., & Turkmen, O. (2022). Use of microbial inoculants against biotic stress in vegetable crops: physiological and molecular aspect. *In* *Sustainable Horticulture* (pp. 263-332). Academic Press.

Chadha, S. (2021). Recent advances in nano-encapsulation technologies for controlled release of biostimulants and antimicrobial agents. *Advances in nano-fertilizers and nano-pesticides in agriculture*, 29-55.

Dawud, I., Bodunrinde, R. E., Oyewole, O. A., Adetunji, C. O., Inobeme, A., Eniola, K. I. T., & Mathew, J. T. (2025). Application of Nanochitosan for Effective Fruit Production. *Nanochitosan Applications for Enhanced Crop Production and Food Security*, 123-135.

Fageria, M.S., Choudhary, B.R., Dhaka, R.S. (2003). Vegetable Crop Production Technology, Kalayni, Publication; II: 75-92.

Hamed, R., Jodeh, S., & Alkowni, R. (2024). Nano bio fertilizer capsules for sustainable agriculture. *Scientific Reports*, *14*(1), 136-146.

Indian Council of Agricultural Research (ICAR). (2022). *Biocapsule technology for biofertilizer delivery*.

R. Hasan, M., N. H. Sani, M., Tahmina, E., & Uddain, J. (2018). Growth and Yield Responses of Cabbage Cultivars as Influenced by Organic and Inorganic Fertilizers. Asian Research Journal of Agriculture, 9(3), 1–12. https://doi.org/10.9734/ARJA/2018/43265

Katyal, S.L., Chadha, K.L. (1985). Vegetable growing in India. Second Edition, Oxford and IBM Publication, New Delhi.

Kim, D. O., Papilla, P. D. and Fl-Zakour, O. I. 2004. Griffith’s flavonoids and antioxidants capacity of various cabbage genotypes at juvenile stage. *Journals of Food Science*, 69: 685-689.

Lalima, V. K. (2023). Effect of Nanochitosan and Biocapsules on Growth, Yield and Quality of Red Okra (*Abelmoschus esculentus* L.).

Latiff, Z. A. A. (2023). Role of chitosan as a foliar applicator towards growth parameter and yield of hydroponic lettuce (*Lactuca sativa* L.). *Empirical Studies of Agro-Based Industry: Volume 3 (Agriculture and Aquaculture)-(Penerbit UMK)*, 21.

Matthews, S. (2020). *Effect of nano-encapsulated bio-stimulant on the growth, yield, and quality of chilli (Capsicum annuum L.)* (Doctoral dissertation, University of Nottingham).

NHB 2020: https://www.nhb.gov.in/

Rai, N. and Yadav, G. D. 2005. Advance in vegetable production. Kalyani publication. p.52.

Rana, S., Thakur, K. S., Bhardwaj, R. K., Kansal, S. and Sharma, R. 2020. Effect of biofertilizers and micronutrients on growth and quality attributes of cabbage (*Brassica oleracea* var. *capitata* L.). *International Journal of Chemical Studies*, 8(1): 1656-1660.

Reddy, R. K., Bahadur, V., & Shukla, P. K. 2024. Effect of various nano formulations of nutrients on soil attributes pre transplanting and post harvesting the crop of cabbage (*Brassica oleracea* var. *capitata*) cv. Pride of India. *International Journal of Advanced Biochemistry Research*; 8(3): 486-492.

Sangwan, S., Sharma, P., Wati, L., & Mehta, S. (2023). Effect of chitosan nanoparticles on growth and physiology of crop plants. In *Engineered nanomaterials for sustainable agricultural production, soil improvement and stress management* (pp. 99-123). Academic Press.

Shahrajabian, M. H., Chaski, C., Polyzos, N., Tzortzakis, N., & Petropoulos, S. A. (2021). Sustainable agriculture systems in vegetable production using chitin and chitosan as plant biostimulants, *Biomolecules*, *11*(6), 819-824.

Shams, A. S. (2019). Foliar applications of nano chitosan-urea and inoculation with mycorrhiza on kohlrabi (*Brassica oleracea* var. *Gongylodes*, L.). *Journal of Plant Production*, *10*(10), 799-805.

Sharma, P., Janaagal, M., Sheoran, A. R., & Sharma, C. (2024). Nanoparticle Innovations in Plant Systems: Enhancing Photosynthesis and Nutrient Dynamics. *Asian Journal of Advances in Agricultural Research*, *24*(12), 75-88.

Waleed, A. (2016). Amelioration of growth and crop performance of cabbage by chitosan foliar spraying under water deficit stress conditions. *Sciences*, *6*(4), 1180-1192.

Wang, X., He, M., Wang, X., Liu, S., Luo, L., Zeng, Q., & Jia, R. (2024). Emerging Nanochitosan for Sustainable Agriculture. *International Journal of Molecular Sciences*, *25*(22), 122-161.

Wani, T. U., Pandith, A. H., & Sheikh, F. A. (2021). Polyelectrolytic nature of chitosan: Influence on physicochemical properties and synthesis of nanoparticles. *Journal of Drug Delivery Science and Technology*, *65*, 102-130.

Devi, Y. Pabitri, and Samir E. Topno. 2022. “Effects of Nano Chitosan and Bio Capsule on Growth, Yield and Quality of Chilli (Capsicum Annuum L.) in Poly-House Condition”. International Journal of Plant & Soil Science 34 (23):662-70. https://doi.org/10.9734/ijpss/2022/v34i232473.

Ma, J., Faqir, Y., Chai, Y., Wu, S., Luo, T., Liao, S., ... & Hadir, W. (2023). Chitosan microspheres-based controlled release nitrogen fertilizers enhance the growth, antioxidant, and metabolite contents of Chinese cabbage. Scientia Horticulturae, 308, 111542.