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The effects of nanobubble fertigation and soil conditioners to improve nutrient dynamics, soil microbial activity, and chili productivity

Abstract. Drip fertigation is a fertilization method that integrates nutrient delivery with an irrigation system, which is capable of optimizing the direct delivery of nutrients to the root zone. This experiment aims to investigate the effect of drip fertigation with nanobubble technology, and soil conditioners on the population of Phosphate-Solubilizing Bacteria (PSB) and *Azotobacter* spp., available phosphorus, total nitrogen, growth, and yield of red chili. The study used a Strip Plot Design with two factors and three replications. The first factor was nutrient application (solid NPK fertilizing as control; drip fertigation; and drip fertigation with nanobubble technology), and the second factor was soil conditioner application (cow manure fertilizer; bioameliorant; and ameliorant). The measured parameters included PSB and *Azotobacter* spp. population, available phosphorus, total nitrogen, growth components (plant height, number of leaves, and stem diameter), and yield components (number of fruits per plant, fruit weight per plant, and yield quality). The results showed that the interaction between drip fertigation with nanobubble technology and soil conditioners significantly influenced the increase in PSB population and available phosphorus. Drip fertigation treatment with nanobubble and ameliorant application gave the best effect on the PSB population and P available. Nutrient application significantly affected plant height, stem diameter, number of fruits per plant, and fruit weight per plant. Soil conditioner application significantly affected total nitrogen, plant height, number of leaves, stem diameter, number of fruits per plant, and fruit weight per plant.

Keywords: Ameliorant · *Azotobacter* · Beneficial microbes · Nutrient · P-solubilizer

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Introduction

Red chili (*Capsicum annuum* L.) is an important vegetable commodity that plays a vital role in both domestic and international markets. Total chili production (red chilies and cayenne peppers) in Indonesia in 2023 was 3.11 million tons. With this high production, Indonesia has good market potential in world trade. According to the Statistics Indonesia (2023), red chili consumption in Indonesia in 2023 was 675 thousand tons. This figure increased from 636.56 thousand tons in 2022 to 596.14 thousand tons in 2021. This indicates that the level of consumption and demand for red chili continues to increase annually. The increase in red chili consumption each year indicates that red chili production needs to be increased to meet consumption needs. Despite continued increases in production, the continued growth in total consumption suggests that domestic red chili supply could still be further increased to reduce dependence on imports.

Meeting the increasing need for red chili consumption can be achieved through the utilization of suboptimal agricultural land, such as Inceptisols soil. Modifying the growing medium through soil conditioners, such as cow manure fertilizer, bioameliorant, and ameliorant, is known to improve the physical and chemical properties of the soil, increase pH, and support soil microbial activity (Avifah et al., 2022; Antonius et al., 2018). The application of liquid nutrients through drip fertigation can support nutrient availability in the root zone. Nutrient solutions are liquid inorganic fertilizers containing essential macro and micro nutrients for plants. Fertigation is a method of nutrient delivery performed simultaneously with irrigation (Kafkafi & Tarchizky, 2011; Yuan et al., 2014). The effectiveness of this system can be enhanced through the integration of nanobubble technology, which involves nano-sized gas bubbles (100–200 nm) that exhibit high stability in water.

Nanobubble technology is known to enhance the solubility of dissolved oxygen and accelerate the release of nutrients in the soil, thereby supporting optimal plant growth (Alqaramah et al., 2025). Phosphorus (P) and nitrogen (N) are two essential macronutrients in plant tissue formation. In addition, soil microbial activity such as phosphate-solubilizing bacteria play an important role in solubilizing P from an unavailable form into a form available to plants (Campos et al., 2018) and *Azotobacter* spp. plays an important role in N fixation (Kholida & Zulaika, 2015). Studies on drip fertigation combined with nanobubble technology and soil conditioners remain limited; therefore, this study aims to determine their effects on the population of phosphate-solubilizing bacteria, available phosphorus, soil nitrogen, and the growth and yield of chili.

Materials and Methods

The experiment was conducted from August to December 2024 at the Bale Tatanen Experimental Field, Faculty of Agriculture, Universitas Padjadjaran, located at an altitude of ± 750 meters above sea level (m asl). The materials used in this study included Inceptisol soil from Jatinangor; red chili seeds of the Baja F1 variety; single inorganic fertilizers comprising urea , SP-36 and KCl; AB mix solution, consisted of stock solution A (LI-A) containing $Ca(NO_3)_2$, KNO_3, and Fe-EDTA, and stock solution B (LI-B) containing KH_2PO_4, $(NH_4)SO_4$, K_2SO_4 (ZK), $MgSO_4.7H_2O$, $CuSO_4$, $ZnSO_4$, H_3BO_3, $MnSO_4$, and Mo-NH_4; cow manure fertilizer; ameliorant, consisted of a mixture of coconut shell biochar, sugarcane bagasse compost, guano, and dolomite; bioameliorant, consisted of a mixture of ameliorant and biofertilizers (phosphate-solubilizing bacteria, nitrogen-fixing bacteria, and *Trichoderma* sp.).

The research conducted pot experiment, used a strip-plot design with two factors and repeated three times. The first factor was nutrient application, consisted of three levels, namely solid NPK fertilizing (as control); drip fertigation; and drip fertigation with nanobubble technology. The second factor was soil conditioner type, consisted of three levels, namely cow manure (20 tons ha^{-1} as control); bioameliorant (4 ton ha^{-1} ameliorant + 200 kg ha^{-1} biofertilizers) and ameliorant (4 ton ha^{-1}).

NPK fertilizer application is side placement by dose 300 kg ha^{-1} urea, 300 kg ha^{-1} SP-36, and 300 kg ha^{-1} KCl given at 3, 6, and 9 weeks after planting (WAP). The volume flowed from drip fertigation with nanobubble technology or without nanobubble technology is 200 ml AB mix solution/polybag. The solution is dripped by concentration 800 ppm (early vegetative stage, from 1 to 2 WAP), 1200 ppm (late vegetative

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stage, from 3 to 4 WAP), and 1600 ppm (generative stage). Soil conditioner is given by side placement, buried in the soil.

Watering is carried out based on the treatment design and its volume is determined based on field capacity. In the NPK treatment, watering is done manually. In the fertigation treatment, watering uses drip fertigation with nutrient solutions. Meanwhile, in the fertigation + nanobubble treatment, watering uses drip fertigation with nanobubble technology. Other plant maintenance were replanting, weeding, and control plant pests and diseases.

Soil samples were collected at the end of the vegetative stage. Rhizosphere soil samples were collected at approximately 100 g for biological analysis, and composite soil samples were collected at approximately 500 g for chemical analysis. The population of phosphate-solubilizing bacteria and *Azotobacter* was calculated using the Total Plate Count (TPC) method, Soil P-Availability measured using the Olsen and Bray I method, for measuring soil nitrogen by Kjeldahl Method.

Growth observations were conducted once a week, starting from 1 week after planting until the plants reached the end of vegetative phase. Measurements included plant height, number of leaves, and stem diameter. In addition, observations were made on the components of chili plant yields, including the number of fruits per plant, the weight of the fruits per plant, and the quality of the chili fruits. All collected data were tabulated in Microsoft Excel and then the data were analyzed using analysis of variance (ANOVA). When significant differences among treatment factors were detected, mean comparisons were performed using Duncan's Multiple Range Test (DMRT) at a 5% significance level.

Results and Discussion

PSB Population. Interactions occur between nutrient application techniques and soil conditioners on PSB populations. The application of drip fertigation using nanobubble technology and soil conditioners results in the best PSB populations (Table 1). Nanobubbles can increase oxygen levels in the root zone, thereby stimulating root growth, improving nutrient uptake, and creating more optimal environmental conditions for beneficial soil microbes (Zhou et al., 2019). This aligns with the statement by Chen et al. (2023), who noted that increased oxygenation due to nanobubbles can influence the activity and population of beneficial soil microbes such as PSB, which play a crucial role in maintaining soil fertility and plant health. Based on Table 1, the treatment of providing drip fertigation nutrients + nanobubbles and soil conditioners in the form of ameliorants gave the best results for the PSB population of 7.12 10^5 x CFU mL^{-1}.

The application of ameliorant containing coconut shell biochar, sugarcane bagasse compost, dolomite, and guano can provide sufficient carbon sources for PSB. The high organic carbon content in coconut shell biochar (Situmorang et al., 2019), sugarcane bagasse compost (Salsavira, 2024), and guano (Yeri et al., 2024) can increase PSB population because organic carbon serves as an energy source for PSB. Previous research showed that ameliorant application of 4 t ha^{-1} combined with nutrient solution can increase PSB population by up to 78.4% compared to the control (Fitriatin et al., 2024).

Table 1. Effect of nutrient applications and soil conditioners interaction on phosphate-solubilizing bacteria population at 6 WAP

Nutrient Application	PSB Population (10^5 CFU mL^{-1})		
	Soil Conditioners		
	Cow Manure Fertilizer	Bioameliorant	Ameliorant
NPK Fertilizer	6.66 a A	6.58 a A	6.73 a A
Drip Fertigation	6.90 a A	6.66 a A	6.65 a A
Drip Fertigation + Nanobubble	6.74 a A	6.77 a A	7.12 b B

Note: Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test at the 0.05 significance level. Capital letters are read horizontally, and small letters are read vertically.

***Azotobacter* spp. Population.** The results showed no interaction between nutrients and soil conditioner application on the *Azotobacter* spp. population (Table 2). High nitrogen availability from readily absorbable nutrient sources can inhibit the nitrogen-fixing activity of *Azotobacter* spp. These free-living, non-symbiotic bacteria typically reduce their nitrogen fixation processes when sufficient nitrogen is already present in the soil. This physiological response is consistent with their ecological role, as *Azotobacter* spp. preferentially activate nitrogen fixation under low-nitrogen conditions to compensate for the deficiency. Consequently, elevated nitrogen levels can suppress both their population density and biological activity (Sheikh Assadi et al., 2023).

Table 2. Effect of nutrient applications and soil conditioners on *Azotobacter* spp. population at 6 WAP

Treatments	*Azotobacter* spp. Population (10^5 CFU mL^{-1})
Nutrient Applications	
NPK Fertilizer	7.02 a
Drip Fertigation	7.11 a
Drip Fertigation + Nanobubble	7.14 a
Soil Conditioners	
Cow Manure Fertilizer	7.05 a
Bioameliorant	7.09 a
Ameliorant	7.12 a

Note: Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test at the 0.05 significance level.

Previous studies have demonstrated that the use of soil conditioners can markedly influence the population dynamics of *Azotobacter* spp. (Table 2). One of the key factors affecting this response is the relatively high carbon-to-nitrogen (C/N) ratio of the applied soil amendments and bio-ameliorants, which in this case was 27.93%. Such an elevated C/N ratio restricts the availability of nitrogen in plant-accessible forms, thereby limiting the proliferation and activity of nitrogen-fixing microorganisms such as *Azotobacter* spp. (Yihune & Addisu, 2024).

Soil P-Availability. Interactions occurred between the application of nutrients and soil conditioners on available phosphorus. The application of drip fertigation using nanobubble technology and ameliorant interacts to produce the best available phosphorus (Table 3). This is likely because ameliorant can support the release of bound phosphorus, while drip fertigation with nanobubble technology enhances nutrient distribution efficiency due to its direct application to the plant root zone. According to Alqaramah et al. (2025), nanobubbles can improve nutrient absorption efficiency by plants and enhance microbial activity in the soil. Increased microbial activity promotes the decomposition and mineralization of organic compounds, and can release a certain amount of phosphorus ions, thereby increasing their availability in the soil (Pang et al., 2024).

This increase in available P is also closely related to the increase in the population and activity of PSB in the soil. This bacteria can produce the enzyme phosphatase, which dissolves organic phosphate into inorganic phosphate through a mineralization process, making P available to plants, especially in soils with low P content (Pan & Cai, 2023).

Table 3. Effect of Nutrient Applications and Soil Conditioners Interaction on Soil P-Availability

Nutrient Applications	Soil P-Availability: Soil Conditioners: Cow Manure Fertilizer	Bioameliorant	Ameliorant
NPK Fertilizer	64.92 c B	29.50 a A	20.19 a A
Drip Fertigation	51.21 b B	19.50 a A	42.28 b B
Drip Fertigation + Nanobubble	16.91 a A	44.41 b B	79.32 c C

Note: Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test at the 0.05 significance level. Capital letters are read horizontally, and small letters are read. vertically

The ameliorant used in this study contained sugarcane bagasse compost and guano. According to Saldaña et al. (2014), the application of bagasse compost can increase the available phosphorus content in the soil due to the release of CO_2 from organic matter, which increases the CO2 concentration in the soil and accelerates the decomposition process of phosphate minerals, thereby increasing the available phosphorus in the soil. The application of guano fertilizer enhances soil organic matter content and improves physical properties, particularly structure and porosity, thereby increasing the availability of essential nutrients such as phosphorus (Lubis et al., 2024).

Total Nitrogen. The results of the analysis showed that there was no interaction between the provision of nutrients and soil conditioners on total N. The analysis reveals that nutrient application exerts variable effects on soil total nitrogen (Total-N) levels, largely shaped by processes such as nitrogen volatilization, nitrate leaching, and plant competition for uptake. Numerous studies have underscored the complexity of nitrogen dynamics in soil systems. For example, Acharya and Shrestha (2015) reported that low soil nitrogen levels can result from rapid plant absorption, coupled with substantial losses through leaching and volatilization. These findings underscore a key characteristic of nitrogen as a highly mobile element, which often escapes the soil matrix rather than being efficiently retained.

Table 4. Effect of nutrient applications and soil conditioners on total Nitrogen

Treatments	Total N (%)
Nutrient Applications	
NPK Fertilizer	0.32 a
Drip Fertigation	0.36 a
Drip Fertigation + Nanobubble	0.39 a
Soil Conditioners	
Cow Manure Fertilizer	0.53 b
Bioameliorant	0.28 a
Ameliorant	0.26 a

Note: Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test at the 0.05 significance level.

The application of cow manure fertilizer had a significant effect on total nitrogen. Based on Table 4, the soil conditioner treatment in the form of manure gave the best results for total N of 0.53%. Cow manure fertilizer contains organic nitrogen that decomposes into an available form (Moe et al., 2019). Increased microbial activity helps to maintain nitrogen in an available form and enriches the soil with total nitrogen (Khodaei Joghan et al., 2010). This is supported by reports showing that the addition of organic matter, such as manure, increases the presence of nitrogen in soluble form in the soil, which in turn enhances nitrogen uptake efficiency by plants (Yang et al., 2018).

Plant Height. The application of drip irrigation, particularly when combined with nanobubble technology, significantly influenced chili plant height at 6 weeks after planting (WAP) (Table 5). Drip fertigation facilitates precise nutrient delivery to the rhizosphere, thereby minimizing fertilizer losses and enhancing nutrient-use efficiency, which ultimately promotes plant growth (Zhao et al., 2023). Moreover, the enrichment of soil oxygen concentration through nanobubble technology has been reported to improve photosynthetic activity, stimulate gibberellin production, regulate microbial dynamics, and further enhance nutrient uptake efficiency (He et al., 2022). The subsequent section presents the documentation of chili plant growth following the application of nutrient inputs and soil amendments at 6 WAP (Figure 1).

Figure 1. Comparison of chili height in response to different nutrient applications and soil conditioners: N1 (NPK Fertilizer), N2 (Drip Fertigation), N3 (Drip Fertigation + Nanobubble), P1 (Cow Manure Fertilizer), P2 (Bioameliorant), and P3 (Ameliorant)

As highlighted by Howe et al. (2024), cow manure is a valuable source of essential nutrients required for plant development, including nitrogen (N), phosphorus (P), and potassium (K), along with various macro- and micronutrients. These nutrients occur in both organic and inorganic fractions, with the organic component undergoing microbial mineralization that gradually releases them into plant-available forms. The efficiency and extent of this mineralization process are largely determined by microbial activity and are strongly influenced by environmental factors such as soil temperature, moisture levels, and the physicochemical characteristics of both the soil and the manure. Beyond the primary nutrients, cow manure also provides secondary nutrients such as calcium (Ca) and magnesium (Mg), as well as trace elements including zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), sulfur (S), and

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boron (B). These nutrients may be available directly in bioavailable forms or as compounds that can be rapidly converted into accessible forms. The integration of cow manure into agricultural practices has consistently been linked with improved soil fertility and enhanced crop productivity (Dhiman et al., 2019).

Number of Leaves. The analysis results show that nutrient application has no significant effect on the number of leaves (Table 6). The nutrient formulations used in this approach are designed to supply both macro- and micronutrients in water-soluble forms, ensuring immediate availability for plant uptake. Among these, nitrogen is the most prominent and plays a vital role in promoting leaf development, as it is integral to photosynthesis and overall vegetative growth (Santana et al., 2021). When combined with nanobubble technology, drip fertigation not only enhances oxygen availability in the rhizosphere but also stimulates root development and supports more robust vegetative growth (Zahra et al., 2025).

The use of cow manure in conjunction with soil ameliorants has been demonstrated to significantly enhance plant growth, notably reflected by an increase in number leaves count at 5–6 WAP. This effect is primarily attributed to the organic matter in cow manure and ameliorants, which improves soil physical properties by enhancing porosity and aeration. Such improvements optimize nutrient availability and uptake—particularly nitrogen—thereby promoting healthier and more vigorous vegetative development (Artacho et al., 2009).

Table 5. Effect of nutrient applications and soil conditioner on chili plant height at 1-6 WAP

Treatments	Plant Height (cm)					
	1 WAP	2 WAP	3 WAP	4 WAP	5 WAP	6 WAP
Nutrient Applications						
NPK fertilizers	25.84	34.14	47.73	67.52	79.46	91.35 a
Drip fertigation	25.32	35.31	49.49	70.29	84.64	98.25 b
Drip fertigation with nanobubble	24.84	36.16	49.97	71.77	85.38	101.77 b
Soil Conditioners						
Cow manure fertilizer	26.25	37.07 b	52.39 b	73.76 b	87.29 b	101.80 c
Bioameliorant	24.84	33.20 a	46.18 a	63.65 a	76.75 a	92.24 a
Ameliorant	24.90	35.35 ab	48.63 ab	72.17 b	85.44 b	97.32 b

Note: Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test at the 0.05 significance level.

Table 6. Effect of nutrient applications and soil conditioner on the number of chili plant leaves at 1-6 WAP

Treatments	Number of Leaves (blades)					
	1 WAP	2 WAP	3 WAP	4 WAP	5 WAP	6 WAP
Nutrient Applications						
NPK fertilizers	11.55	17.70	33.88	73.14	115.18	173.63
Drip fertigation	12.11	17.66	35.11	78.11	115.33	162.55
Drip fertigation with nanobubble	12.14	18.25	38.88	76.40	128.07	181.40
Soil Conditioners						
Cow manure fertilizer	12.37 a	18.77 b	40.81 b	87.59 b	138.07 b	190.74 b
Bioameliorant	11.51 a	16.70 a	30.70 a	65.48 a	94.14 a	143.85 a
Ameliorant	11.92 a	18.15 ab	36.36 ab	74.59 ab	126.37 b	183.00 b

Note: Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test at the 0.05 significance level.

Stem Diameter. The application of drip fertigation and drip fertigation with nanobubble technology had a significant effect on stem diameter (Table 7). This technique optimizes the supply of both macro- and micronutrients, thereby supporting essential physiological processes required for vigorous plant growth. Among these nutrients, nitrogen is particularly crucial, as it stimulates the development of vegetative structures, including stems, which play a fundamental role in sustaining overall plant performance (Dianawati et al., 2023). The application of drip irrigation with nanobubble technology enhances gas transport efficiency to cells, improves membrane structure and protein activity, thereby supporting stem growth (Liu et al., 2013; Seddon et al., 2012).

The incorporation of cow manure together with soil ameliorants has been shown to substantially promote plant growth, as indicated by a significant increase in stem diameter at 3–4 weeks after planting (WAP). This effect is primarily associated with the high organic matter content of cow manure and ameliorants, which improve soil physical properties by enhancing porosity and aeration. Such improvements facilitate more efficient nutrient dynamics, particularly nitrogen uptake, thereby stimulating vigorous vegetative growth (Artacho et al., 2009).

Number of Fruits per Plant. The combination of drip fertigation and nanobubble technology has been shown to markedly improve fruit production in crop systems (Table 8). Drip fertigation ensures the precise and efficient delivery of macro- and micronutrients in soluble forms, facilitating rapid uptake by plants. When coupled with nanobubbles, this system further enhances nutrient utilization and physiological efficiency, particularly during the generative phase of developm ent. In fruiting crops such as chili peppers, these synergistic effects translate into a significant increase in yield (Giri et al., 2024). Nanobubble formulations enhance nutrient absorption efficiency through controlled-release mechanisms (Zhou et al., 2019).

Table 7. Effect of Nutrient Applications and Soil Conditioners on Chili Plant Stem Diameter at 1-6 WAP

Treatments	Stem Diameter (mm)					
	1 WAP	2 WAP	3 WAP	4 WAP	5 WAP	6 WAP
Nutrient Applications						
NPK fertilizers	3.67	4.40	5.31	6.60	7.46	8.57 a
Drip fertigation	3.68	4.36	5.52	7.00	7.74	9.44 b
Drip fertigation with nanobubble	3.75	4.59	5.55	7.03	7.57	9.68 b
Soil Conditioners						
Cow manure fertilizer	3.67	4.34	5.80 b	7.27 b	8.00	9.58
Bioameliorant	3.71	4.37	5.21 a	6.57 a	7.25	8.95
Ameliorant	3.72	4.63	5.38 ab	6.80 ab	7.52	9.16

Note: Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test at the 0.05 significance level.

Table 8. Effect of Nutrient Applicationss and Soil Conditioner on the Number of Fruits per Plant

Treatments	Number of Fruits per Plant
Nutrient Applications	
NPK Fertilizer	37.07 a
Drip Fertigation	31.59 a
Drip Fertigation + Nanobubble	48.44 b
Soil Conditioners	
Cow Manure Fertilizer	47.59 b
Bioameliorant	28.77 a
Ameliorant	40.74 b

Note: Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test at the 0.05 significance level.

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The application of cow manure combined with soil ameliorants has been demonstrated to significantly increase the number of fruits per plant. This improvement is associated with the abundant supply of key nutrients, particularly nitrogen (N), phosphorus (P), potassium (K), and organic carbon, which collectively enhance plant vigor and productivity. These elements are essential for cellular development and carbohydrate metabolism (Ogundare et al., 2015). Among them, phosphorus is especially critical, as it is absorbed predominantly in the form of hydrogen phosphate (HPO_4^{2-}) and dihydrogen phosphate ($H_2PO_4^-$) ions. These soluble species represent the most plant-available forms of phosphorus in the soil solution and are primarily taken up through diffusion (Wang et al., 2024). The efficiency of phosphorus absorption is strongly regulated by soil pH, with the optimal range for uptake typically between 4.5 and 5.0. Within this range, plants preferentially utilize $H_2PO_4^-$, emphasizing the importance of maintaining suitable soil pH conditions for effective nutrient management (García et al., 2025).

Fruit Weight per Plant. The application of drip fertigation with nanobubble technology has a significant effect on fruit weight per plant (Table 9). The application of drip fertigation integrated with nanobubble technology has a pronounced effect on fruit weight per plant. This system enhances the precision and efficiency of nutrient delivery, thereby supporting the biosynthesis of proteins, carbohydrates, and lipids that are fundamental to fruit development and weight accumulation (Camarero et al., 2023). The improved nutrient availability promotes optimal metabolic functioning within the plant, ensuring that assimilates are efficiently allocated to developing fruits. Potassium (K), in particular, plays a pivotal role as a macronutrient influencing plant growth, physiology, and yield. Acting as a key enzyme activator, potassium regulates numerous biochemical processes, including photosynthesis, osmotic balance, and assimilate transport. Given its high uptake demand—second only to nitrogen—potassium is indispensable for sustaining physiological efficiency and maximizing fruit production (Al-Raddadi et al., 2024). Nanobubbles enhance oxygen availability in the root zone, support root respiration, and improve water and nutrient absorption efficiency, thereby supporting fruit filling and weight increase (Wu et al., 2019).

Table 9. Effect of nutrient applications and soil conditioners on fruit weight per plant

Treatments	Fruit Weight per Plant (g)
Nutrient Applications	
NPK Fertilizer	177.90 a
Drip Fertigation	174.47 a
Drip Fertigation + Nanobubble	261.91 b
Soil Conditioners	
Cow Manure Fertilizer	250.07 b
Bioameliorant	160.14 a
Ameliorant	204.14 ab

Note: Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test at the 0.05 significance level.

The use of cow manure has been shown to significantly increase fruit weight per plant, mainly due to its rich composition of macro- and micronutrients, particularly N, P, and K, which are essential for protein synthesis, assimilate production, and fruit tissue development. In addition to nutrient supply, cow manure contributes substantial organic matter that enhances soil fertility, structural stability, and water retention capacity. These improvements foster better root growth and nutrient uptake, ultimately resulting in higher crop productivity (Ikeh et al., 2023). Furthermore, its ability to improve soil water absorption enhances nutrient uptake efficiency, thereby supporting optimal fruit growth.

Quality of Chili Yields. Irrigation with nanobubble-enriched water significantly improves the quality of chili fruits, with grade I peppers showing up to a 14.45% increase in fruit quality compared to conventional fertilization using urea, SP-36, and KCl. The macro- and micronutrients delivered through drip irrigation play a critical role in meeting plant nutritional demands for producing high-quality fruit. Potassium, in particular, is an essential macronutrient that supports growth and enhances fruit quality (Meylia & Koesriharti, 2018). Moreover, nanobubbles improve irrigation efficiency by increasing nutrient uptake and water-use efficiency, thereby boosting crop yield and fruit quality without requiring additional water or fertilizer inputs (Liu et al., 2019).

Table 10. Effect of nutrient applications and soil conditioners on chili quality

Treatments	Yield Quality (%)					
	I	II	Good Quality (I+II)	Improvement in Quality (I+II) (%)	III	BS
Nutrient Applications						
NPK fertilizers	5.63 a	59.98	65.61	-	30.20	4.19
Drip fertigation	8.30 a	65.36	73.66	12.27	20.85	5.49
Drip fertigation with nanobubble	14.96 b	60.13	75.09	14.45	20.26	4.65
Soil Conditioners						
Cow manure fertilizer	6.36	64.71	71.07	-	24.57	4.36
Bioameliorant	13.56	60.81	74.37	4.64	20.51	5.12
Ameliorant	8.98	59.94	68.92	-3.03	26.23	4.85

Note: Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test at the 0.05 significance level.

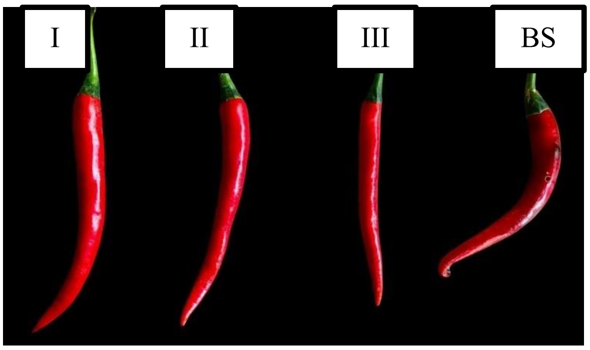

Figure 2. Comparison of Chili Quality in Response to Different Nutrition and Soil Conditioners: I (Premium), II (Medium), III (Standard), BS (Below Standard)

The chili classification system categorizes chili fruits into four quality grades, ranging from Grade I to Below Standard (Figure 2). This grading is primarily based on external attributes such as color uniformity, shape and size consistency, cleanliness, and the presence of physical damage or decay. Higher grades are characterized by uniform red coloration, typical fruit morphology, and minimal defects or contamination. In contrast, lower grades display reduced uniformity, irregular or undersized fruits, and a greater incidence of visible dirt, damage, or deterioration.

Table 10 shows soil conditioner with bioameliorants indicates an 4.64% improvement in fruit quality (I+II) compared to the application of cow manure. This is because the bioameliorants used in this study contain guano and biological agents. The high phosphorus content in guano fertilizer plays an important role in fruit quality formation and increases plant resistance to disease (Taofik et al., 2018). Biological agents can improve soil structure and increase nutrient absorption, thereby supporting optimal plant growth and producing fruit of better quality (Nicolson et al., 2021). This finding is consistent with the results of Widiantini et al. (2022), who reported that biological agents such as *Trichoderma* sp. and *Pseudomonas fluorescens* significantly improved dragon fruit quality and increased yield by up to 30%.

Conclusion

The interaction between drip fertigation with nanobubble technology and soil conditioners had a significant effect on increasing the population of PSB and available P. Nutrient treatment has a significant effect on plant height at 6 WAP, stem diameter at 6 WAP, and the quality of chili peppers of grade I. Soil conditioner treatment has a significant effect on plant height at 2–6 WAP, number of leaves at 3–6 WAP, stem diameter at 3–4 WAP, number of fruits per plant, and fruit weight per plant.

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