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Research Article

Integration of nanobubble-driven drip fertigation and soil conditioner in enhancing some of soil chemical–biological responses, chili growth, yield and quality

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Abstract

Nanobubble-driven drip fertigation and soil conditioners are increasingly applied to enhance red chili productivity, a key Indonesian cash crop with high economic value but limited export competitiveness. This integration improves water and nutrient delivery, increases dissolved oxygen, and enhances soil properties, thereby supporting better growth, yield, and quality. This study aims to examine the synergy of nanobubble-driven drip fertigation and soil conditioners in enhancing soil chemical–biological properties, as well as the growth, yield, and quality of red chili. The experiment used a strip-plot design with two factors, namely nutrient source (NPK, drip fertigation, and drip fertigation + nanobubble) and type of soil conditioner (manure, bioameliorant, and ameliorant), each with three replications. Observed parameters included pH, organic carbon, total nitrogen, available phosphorus, phosphate -solubilizing bacteria (PSB) and nitrogen-fixing bacteria (NFB), growth, yield, and fruit quality. The results showed a significant interaction between nutrients and soil conditioner on PSB populations, P availability, fruit number, fruit weight per plant, and fruit quality. The drip fertigation + nanobubble treatment increased fruit weight by 299.18 g/plant (39.77%) and fruit number by 59.25 g/plant (34.1%) compared to the NPK and manure treatment. The PSB population, plant height, and stem diameter positively contributed to fruit weight, while stem diameter, plant height, and chlorophyll content were positively related to fruit number. Furthermore, increasing soil pH correlated with an increase in the proportion of fruit quality categories A and B. Overall, the pH and organic carbon variables directly influenced the increase in good fruit quality (A+B) by 39.5%.

Keywords: Drip irrigation, Horticulture, Soil improver, Nanobubble technology, Cash crop

Introduction

Red chili (*Capsicum annuum* L.) is a strategic cash crop in Indonesia, playing a central role in household consumption, agribusiness, and national food security. Beyond its cultural importance as a staple in daily diets, chili farming contributes substantially to rural livelihoods and farmers' income. However, despite its socio-economic significance, Indonesia continues to face challenges in maintaining competitiveness in the international chili market. Yields are often inconsistent, fruit quality is suboptimal, and the crop remains highly vulnerable to biotic and abiotic stresses (Tripathi *et al.,* 2025).

One promising pathway is the integration of advanced fertigation technologies with soil management practices that enhance the quality of the soil medium. Drip fertigation, which delivers water and nutrients directly to the root zone, has been widely recognized for its efficiency in resource use and its ability to improve nutrient uptake while reducing losses (Rezaei *et al.,* 2025). More recently, the incorporation of nanobubble technology into drip fertigation has drawn attention. Nanobubbles, with their high stability and capacity to elevate dissolved oxygen levels in irrigation water, have been shown to enhance nutrient absorption, root activity, and soil microbial processes (Balea *et al.,* 2026). Together, drip fertigation and nanobubbles can optimize the plant–soil–water interface, creating a favorable environment for crop growth and productivity.

Equally important is the use of soil conditioners to improve soil chemical–biological properties and restore degraded soils. Soil degradation remains a major challenge in chili production systems, especially under simple plastic house structures where intensive management often relies heavily on inorganic fertilizers. Prolonged use of such inputs depletes organic matter, increases soil acidity, and deteriorates soil structure, resulting in reduced soil fertility, lower microbial biodiversity, and yield decline. By enhancing soil media quality, soil conditioners such as ameliorants, bioameliorants, compost, and organic manures play a vital role in sustaining productivity and supporting environmentally friendly chili cultivation (Setiawati *et al.,* 2023).

Different types of soil conditioners can be employed to address various soil constraints. Ameliorants such as lime or gypsum are commonly used to neutralize soil acidity, alleviate aluminum and iron toxicity, and enhance cation exchange capacity, thereby creating a more favorable chemical environment for plant roots (Ismail *et al.,* 2025). Bioameliorants, which include microbial inoculants and beneficial soil microbes, play an equally important role in promoting nutrient mineralization, fixing atmospheric nitrogen, solubilizing phosphorus, and suppressing soil-borne pathogens (Setiawati *et al.,* 2023). Compost and organic manures contribute organic matter that enhances soil structure, water-holding capacity, and microbial diversity, all of which support improved nutrient cycling and long-term soil fertility (Singh *et al.,* 2024). Recent studies emphasize that integrated use of organic conditioners improves both soil physical quality and crop yield performance compared to sole reliance on chemical fertilizers (Zeiner *et al.,* 2024).

Drip fertigation enriched with nanobubbles provides a synergistic advantage by ensuring precise delivery of water and nutrients while simultaneously improving oxygen availability at the root zone. This integrated approach reduces nutrient leaching, enhances water-use efficiency, and supports robust plant physiological activity. When soil conditioners are incorporated into the system, they provide organic matter and beneficial compounds that interact positively with improved soil aeration and microbial activity, leading to stronger root growth, enhanced nutrient uptake, and higher tolerance to environmental stress (Tinaprilla *et al.,* 2024; Ray *et al.,* 2025). Such synergies are particularly relevant for chili cultivation, where root vigor and soil fertility strongly influence fruit set, yield stability, and post-harvest quality.

Given the strategic role of red chili in Indonesian agriculture, improving its productivity and quality through integrated soil–water management systems is timely and essential. By addressing soil degradation, enhancing nutrient-use efficiency, and strengthening soil biological processes, the synergy of nanobubble-driven drip fertigation and soil conditioners can significantly advance chili farming toward greater sustainability and competitiveness. This integration not only supports higher domestic supply and food security but also offers potential to improve export quality and value. The study aims to evaluate the impact of combining nano-bubble-enhanced drip irrigation with soil conditioners on improving soil properties and red pepper yields, with a view to developing sustainable agricultural systems in Indonesia.

Materials and methods

The experiment was conducted at the Bale Tatanen experimental field, Faculty of Agriculture, Universitas Padjadjaran, West Java, Indonesia. The site is situated at an altitude of approximately 750 meters above sea level (masl), with geographic coordinates of 6°55′12.2″ S and 107°46′24.3″ E (–6.9200431, 107.7734243). Initial and final soil analysis was conducted at the Soil Chemistry-Fertility and Plant Nutrition Laboratory and the Soil Biology Laboratory, Department of Soil Science and Land Resources, Faculty of Agriculture, Padjadjaran University.

The soil used in this experiment was Inceptisols from Jatinangor with the following chemical properties: pH of 5.83 which is classified as slightly acidic, organic C content of 1.30% which is considered low, C/N ratio of 6.20 which is also low, total nitrogen (N-total) of 0.21% which is categorized as moderate, available phosphorus (P-available) of 10.8 ppm which is classified as low, and potential phosphorus (P-potential) of 22.86 mg/100 g which is considered moderate (Table 1). The chili variety used in this study was the Baja F1 variety.

The nutrients used are NPK, and nutrient solution with Nutrient Solution A and B. The soil conditioner used in this study is, manure with a dose of 20 t ha^{-1}, ameliorant with a dose of 4 t ha^{-1} with a composition of sugarcane blotong compost (50%), coconut shell biochar (30%), dolomite (10%), and guano (10%), and bioameliorant (ameliorant with a dose of 4 t ha^{-1} + Biofertilizer with a dose of 208 kg ha^{-1}) the biofertilizer used is *Trichoderma* sp. with a density of 3.55x105 CFU g^{-1} enriched with biofertilizers, namely (Nitrogen-Fixing Bacteria (*Azotobacter* sp. & *Azospirillum* sp.) with a density of 1x10^{7} CFU g^{-1} and Phosphate-Solubilizing Bacteria (*Pseudomonas* sp. & *Bacillus* sp.) with a density of 2x10^{7} CFU g^{-1}. Nanobubble fertigation is applied by mixing the stock solutions A and B, then administered through a drip fertigation system with gradual concentrations, namely 800 ppm (1-2 WAP), 1,200 ppm (3-4 WAP), and 1,600 ppm in the generative phase.

Before being distributed to the plants, the nutrient solution is aerated using a nanobubble generator consisting of an AIRLUX UP 200 submersible pump (150 watts; capacity 250 L/min) and a rotating Plexiglas nozzle, producing bubbles of average size 54.47 nm. This process utilizes oxygen from the surrounding air, pumped at high pressure, creating a spiral flow and centrifugal force, which is then compressed to form nanobubbles measuring <200 nm. A 30-minute operation increase dissolved oxygen (DO) from 5 mg L^{-1} to 6.5 mg L^{-1}, with a significant increase in the first five minutes and a plateau after 30 minutes. The oxygenated nutrient solution supplied to the polybags via drip fertigation at 200 mL per plant for 10 minutes, with DO checks conducted weekly.

Experimental design

The experimental design used was a strip-plot design consisting of two factors. In the strip-plot, the parent plot is located in a vertical strip, while the subplots are in a horizontal strip. The parent plot were the nutrient

Table 1: Pre-experiment soil chemical analysis

Soil properties	Value
pH H_2O (%)	5.83
Base saturation (%)	23.68
C-organic (%)	1.30
N (%)	0.21
C/N	6.20
P-Potential (mg/100 g)	22.86
P-available (ppm)	10.8
K-Potential (mg/100 g)	18.61
K-dd (mg/100 g)	0.55
Ca-dd (mg/100 g)	4.82
Mg-dd (mg/100 g)	0.54
Na-dd (mg/100 g)	0.04
Al-dd (ppm)	0.12
H-dd (ppm)	0.21
CEC (cmol/kg)	25.13

application, which consists of three levels i.e., NPK fertilizer (300 kg urea, 300 kg SP-36, and 300 kg KCl) applied at 3, 7, and 11 weeks after planting as the control treatment; Drip Fertigation (Daily application, 200 mL volume) until harvest; Drip Fertigation + Nanobubble (Daily application, 200 mL volume). Subplots were soil conditioner applied at three levels i.e. manure (20 t ha^{-1}); bioameliorant (ameliorant 4 t ha^{-1} + biofertilizer 208 kg ha^{-1}); ameliorant (4 t ha^{-1}).

The observed responses were: PSB population using the Total Plate Count (TPC) method; NFB population using the Total Plate Count (TPC) method; Organic C content analysis using the Walkey and Black method; pH; soil N using the Kjeldahl method; soil Available P using the Olsen or Bray methods; Chlorophyll content of leaf using a spectrophotometer; growth and yield of red chili.

Statistical and calculation methods

The data obtained were analyzed using SPSS with the Shapiro-Wilk normality test stage, followed by analysis of variance (ANOVA), and if there were significant differences between treatments, a further Duncan's Multiple Range Test (DMRT) was performed at the 5% level. Soil chemical-biological properties (organic C, pH, total N, available P, NFB and PSB populations), growth (plant height, stem diameter, number of leaves), and fruit yield and quality (fruit weight/plant, number of fruits/plant, quality A, B, C, BS, and A+B) were analyzed using Pearson correlation to see the relationship between variables. A positive correlation coefficient (r) value indicates a unidirectional linear relationship, while a negative value indicates an inverse relationship, with the level of relationship strength categorized from very weak to very strong. Variables that showed a significant correlation were then analyzed using stepwise regression to determine the factors that most influenced the yield components (Badri *et al.,* 2016).

Results and discussion

Soil biological properties phosphate-solubilizing bacteria (PSB) and Nitrogen-fixing bacteria (NFB)

Nutritional application through drip fertigation plus nanobubbles and ameliorants yielded the best results for the phosphate-solubilizing bacteria (PSB) population, reaching 7.12 x 10^5 CFU mL^{-1} (Table 2). This combination creates a supportive environment for increasing the population and activity of soil microbes, particularly PSB. Drip fertigation ensures the distribution of essential nutrients to the root zone, while nanobubbles increase dissolved oxygen levels, which are essential for microbial respiration. Ameliorants improve the physical condition of the soil and provide an energy source, thus supporting the growth of microorganisms.

Table 2: Effect of nutrient and soil conditioners provision on PSB population

	PSB10^5 x CFU mL^{-1}		
Nutrients	**Soil conditioners**		
	Manure	**Bioameliorant**	**Ameliorant**
NPK	6.55^{aA}	6.58^{aA}	6.73^{aB}
Drip fertigation	6.90^{bB}	6.80^{bB}	6.58^{aA}
Drip fertigation + Nanobubble	6.74^{abA}	6.77^{aA}	7.12^{bB}

The average value followed by the same letter is not significantly different according to Duncan's Test at a significance level of 0.05. Lowercase letters are read vertically, capital letters are read horizontally

Ameliorants containing coconut shell biochar can increase soil microbial activity and populations. The high organic carbon content of biochar can be utilized as an energy or food source, and improves the living conditions of soil microorganisms (Fitriatin *et al.,* 2024). Therefore, adding biochar-containing ameliorants to the soil can increase the population of soil microorganisms (Ighalo *et al.,* 2025). Additionally, ingredients such as sugarcane filter cake compost and guano can provide energy sources for soil microbes, and dolomite can maintain a neutral pH, supporting increased activity and populations of functional soil microbes (Khan *et al.,* 2024).

The analysis results showed no interaction between nutrient treatment and soil conditioners. However, there was an independent effect of nutrient treatment on NFB population. According to Figure 1 the nutrient treatment in the form of drip fertigation resulted in a high NFB population, but not significantly different from the drip fertigation + nanobubbles.

The effect of drip fertigation treatment has been shown to support an increase in the NFB population (Table 3). Nutrient solutions contain essential elements such as KH_2PO_4, KNO_3, and $MgSO_4 \cdot 7H_2O$, which play

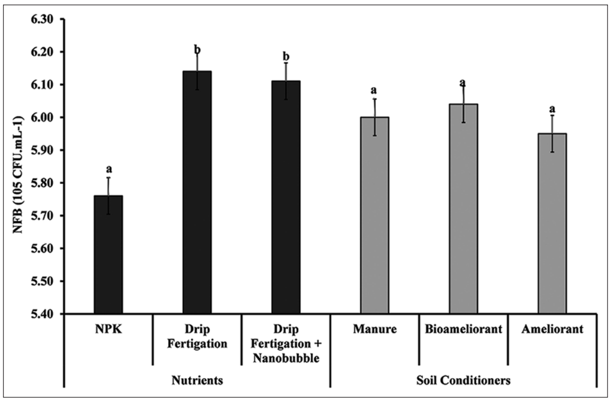


Figure 1: Effect of nutrient and soil conditioners on NFB population

Table 3: Effect of nutrient and soil conditioners on NFB population

Nutrients	**10^5 CFU mL^{-1}**
NPK	5.76^a
Drip fertigation	6.14^b
Drip fertigation+Nanobubble	6.11^b
Soil conditioners	
Manure	6.00^a
Bioameliorant	6.04^a
Ameliorant	5.95^a

The average value followed by the same letter is not significantly different according to Duncan's Test at a significance level of 0.05

a crucial role in increasing the NFB population by providing essential nutrients and supporting metabolism and plant-microbe interactions in the rhizosphere zone. The phosphorus content in KH_2PO_4 plays a crucial role in bacterial metabolic processes, such as energy transfer, signal transduction, and nitrogen fixation (Ma *et al.,* 2021). In addition, phosphorus accelerates root development and carbohydrate production in the form of root exudates, which attract bacteria to the rhizosphere, facilitating symbiotic plant-microbe interactions (Upadhyay *et al.,* 2025). According to Wang *et al.* (2021), this interaction is initiated by plants through the secretion of exudates that actively invite them to approach and colonize the roots. Root exudates in the rhizosphere can influence soil microbial communities and the availability of macro- and micronutrients, particularly nitrogen and phosphorus (Chauhan *et al.,* 2023).

KNO_3 and $MgSO_4 \cdot 7H_2O$ in nutrient solutions also contribute to microbial activity and populations. The nitrate (NO_3^-) and potassium (K^+) in KNO_3 serve as essential nutrients that support microbial cell growth, while magnesium (Mg^{2+}) from $MgSO_4 \cdot 7H_2O$ acts as an enzymatic cofactor, crucial for various biochemical processes within microbial cells, including enzymes involved in nitrogen fixation (Shahreyar *et al.,* 2019). Mo-NH_4 acts as a catalyst, activating the nitrogenase enzyme, thus contributing to nitrogen fixation by NFB (Harris *et al.,* 2018). The combination of nutrients in the nutrient solution delivered through drip fertigation creates an optimal environment for nitrogen-fixing bacteria, both through direct metabolic support and through enhanced plant-microbe interactions, thereby synergistically increasing the bacterial population in the rhizosphere.

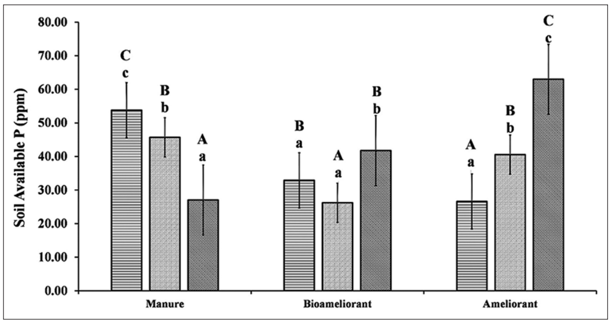


Figure 2: Effect of nutrient and soil conditioners application on soil available P

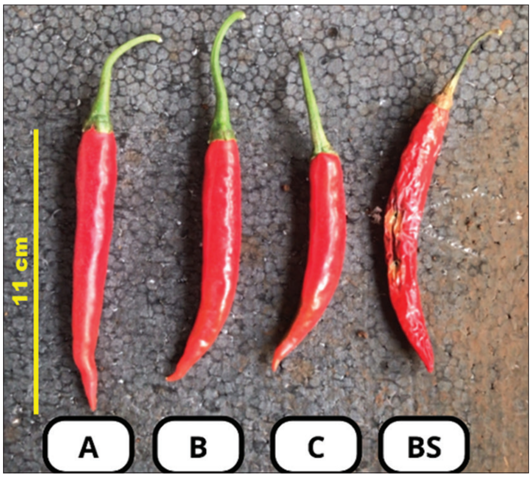


Figure 3: Quality of red chilies grade A, B, C, and BS

Chemical properties of soil

The results of the analysis of variance at the 5% level indicated an interaction between nutrient application and soil conditioners on available P in the soil. Further testing revealed that the interaction of drip fertigation + nanobubble and conditioners provided the best results for available P, at 62.99 ppm (Figure 2).

The interaction of drip fertigation + nanobubbles and ameliorants has been shown to increase available P in the soil. The oxygen produced by nanobubbles improves soil environmental conditions by increasing soil microbial activity, which plays a role in converting nutrients into forms more readily absorbed by plants. This is in line with the statement by Zhou *et al.* (2022), who stated that oxygenated soil can increase available P content and alter the composition of soil bacterial communities. Furthermore, oxygenated irrigation can increase soil microbial diversity and nutrient transformation rates, significantly increasing the concentration of available phosphorus in the soil and strengthening the metabolic relationships of microbes in the root zone (Wu *et al.,* 2019; Qian *et al.,* 2022).

The dolomite content in ameliorants plays a crucial role in this regard, improving soil structure, increasing CEC, and reducing the rate of phosphate fixation by Al^{3+} and Fe^{3+} ions in acidic soils. Dolomite specifically functions as a liming agent that can increase the pH of acidic soils, thereby releasing phosphorus from Al-P and Fe-P bonds, and reducing the potential for Fe, Mn, and Al toxicity (Vondráčková *et al.,* 2013).

Based on the results of the analysis of variance at the 5% level, no interaction was found between nutrient and soil conditioners treatments on pH, organic carbon, and total soil nitrogen (Table 4). However, there was an independent effect of soil conditioners treatments on soil pH, organic carbon, and total nitrogen.

The application of ameliorant and bioameliorant was significantly different when compared to the manure

Table 4: Effect of nutrient and soil conditioner application on soil chemical properties

Treatments	pH	Organic Carbon (%)	Total soil N (%)
Nutrients			
NPK	6.44^a	2.84^a	0.39^a
Drip fertigation	6.24^a	2.96^a	0.36^a
Drip fertigation+Nanobubble	6.36^a	2.65^a	0.32^a
Soil conditioners			
Manure	5.82^a	3.68^b	0.54^b
Bioameliorant	6.58^b	2.50^a	0.28^a
Ameliorant	6.64^b	2.27^a	0.26^a

The average value followed by the same letter is not significantly different according to Duncan's Test at a significance level of 0.05

treatment, which resulted in a pH of 5.82. This indicates that the use of ameliorant is more effective in neutralizing soil acidity than other soil conditioners. This is in line with the results of research by Saputra and Sari (2021), which found that ameliorant application can increase soil pH. This increase in soil pH is crucial for increasing nutrient availability and improving plant root growth conditions.

One of the organic materials contained in ameliorants and bioameliorants is dolomite. Dolomite is used as a soil additive to increase or stabilize soil pH. Dolomite added to the soil can increase soil pH, organic carbon, and bacterial activity (Wu *et al.,* 2021). Pure dolomite contains 21.7% and 13.04% Ca and Mg, respectively (Edahwati *et al.,* 2024). Calcium (Ca) and magnesium (Mg) can undergo hydrolysis reactions, producing OH^- ions. These OH^- ions play a role in increasing soil pH by neutralizing soil acidity (Zhang, 2024).

The increase in organic carbon content in the manure treatment is closely related to manure's nature as a source of carbon-rich organic matter. The increase in organic carbon content in the soil due to the application of cow manure is caused by the decomposition process of cow manure, which releases various carbon compounds. This carbon compound is a major component of organic matter (Denoncourt *et al.,* 2025). Therefore, the addition of cow manure directly contributes to increasing the organic C content in the soil. Manure also improves soil physical properties such as soil structure, water retention capacity, permeability, porosity, and cation concentration (Rayne & Aula, 2020).

In addition to the type of material, the higher dose of manure (20 t ha^{-1}) in the manure treatment compared to the conditioners dose in the bioameliorant and ameiliorant treatments (4 t ha^{-1}) is thought to be an important factor contributing to the increase in organic C levels. The greater the amount of organic matter added to the soil, the greater its contribution to increasing organic C. This finding aligns with the statement by Xu *et al.* (2025), who stated that increasing fertilizer doses is always followed by an increase in soil organic C. Therefore, the greater the addition of cow manure doses, the greater the increase in soil organic C.

The high levels of total N in manure treatment can originate from the mineralization/decomposition of the applied organic matter or from plant roots (Chiriac *et al.,* 2025). The organic matter contained in manure increases the total N in the soil. This is because organic matter releases nitrogen and other compounds, thus optimizing nutrient absorption and photosynthesis (Xing *et al.,* 2025). Furthermore, Idham *et al.* (2021) found that high-dose manure application (10-20 t ha^{-1}) significantly improved the condition of the growing medium by chemically contributing nutrients, reducing N leaching, and significantly increasing total N. Research by Denoncourt *et al.* (2025) found that manure application can increased total N in soil. However, not all organic N from manure was fully converted into plant-available N.

Growth characteristics

Based on the results of the analysis of variance at the 5% level, no interaction was found between nutrient and soil conditioners treatments on growth characteristics. However, nutrient treatment showed an independent effect on all growth characteristics parameters yielded the highest values across all measured growth parameters relative to the other treatments. Nevertheless, the differences observed in plant height and stem diameter were not statistically significant when compared with the drip-fertigation-only treatment. In contrast, for leaf number, the drip fertigation + nanobubble treatment exhibited a statistically significant increase relative to all other treatments. However, there was an independent effect on leaf chlorophyll from nutrient application. Based on the analysis, drip fertigation + nanobubbles had the best effect on leaf chlorophyll yield (Table 5).

The independent effect of nutrient treatment, namely, drip fertigation + nanobubble produced the highest plant height, followed by drip fertigation, and NPK.

Plant height is influenced by the availability of essential nutrients. The nutrient solution in drip fertigation contains nutrients that can support plant growth, including nitrogen and phosphorus. The N and P content in the nutrient solution and NPK can increase plant height. This aligns with the statement by Zeng *et al.* (2022), who stated that nitrogen and phosphate play a crucial role in stimulating plant growth. Furthermore, the KNO_3 nutrient in drip fertigation contains nitrogen and potassium, which activate gibberellins, activate dormant buds, and enhance plant growth (Alebidi *et al.,* 2023).

The integration of nanobubbles in drip fertigation enhances root activity through a more stable oxygen supply, ultimately accelerating the absorption of nitrogen,

Table 5: Effect of nutrient and soil conditioner application on plant height, number of leaves, stem diameter, and chlorophyll

Nutrients	Parameters			
	Plant height (cm)	Number of leaves	Stem diameter (mm)	Chlorophyll (mg L^{-1})
NPK	90.73^{a}	175.39^{a}	8.25^{a}	1.16^{b}
Drip fertigation	100.83^{b}	169.71^{a}	9.52^{b}	1.01^{a}
Drip fertigation+Nanobubble	103.08^{b}	200.57^{b}	9.74^{b}	1.27^{c}
Soil Conditioners				
Manure	96.28	167.90^{a}	8.96^{a}	1.08^{a}
Bioameliorant	98.08	171.35^{a}	9.21^{a}	1.17^{a}
Ameliorant	100.27	206.42^{b}	9.34^{a}	1.20^{a}

The average value followed by the same letter is not significantly different according to Duncan's Test at a significance level of 0.05

phosphorus, and potassium, supporting plant growth. Previous research on the use of nanobubbles for nutrient application in hydroponic spinach and hydroponic red lettuce showed increased plant growth, such as plant height (Putri *et al.,* 2023). Wu *et al.* (2019) also found that nanobubble treatment significantly increased plant height in tomato plants due to increased available nitrogen and phosphorus in the soil, as well as increased microbial activity and population. Furthermore, another study found that nanobubble oxygen application significantly increased plant growth, specifically plant height, by 30-50% (Xue *et al.,* 2023).

Fulfilling plant nutrient needs through drip fertigation + nanobubbles can support plant leaf growth. This is in accordance with the statement by Vargas *et al.* (2023) that sufficient nutrient availability will stabilize the increase in leaf number. $Ca(NO_3)_2$ in the drip fertigation nutrient solution contains K and N nutrients, which function to regulate the opening and closing of stomata, chlorophyll synthesis, protein and amino acids, and play a role in the growth of new shoots (Ren *et al.,* 2025). Nitrogen is very important in the process of photosynthesis so that the higher the element contained, the more photosynthate leaves are produced (Shah *et al.,* 2024). Nanobubbles can increase the number of leaves in plants due to the presence of dissolved oxygen which helps increase plant growth.

The essential nutrients in drip fertigation with nanobubbles can increase plant stem diameter growth. This is in line with the statement by Pangalila *et al.* (2023), who stated that essential nutrients such as N, P, and K absorbed by plants will stimulate stem diameter enlargement. Furthermore, nanobubbles can increase stem diameter growth due to more optimal water and nutrient absorption due to oxygen dissolution in the soil. This is in line with previous research showing that irrigation with nanobubble technology results in increased plant stem diameter growth through increased nutrient uptake by plants (Pal & Anantharaman, 2022). The efficient use of water due to the addition of nanobubbles is also a contributing factor to stem diameter growth. Nanobubble application improves soil structure by increasing total porosity and pore connectivity, thereby facilitating better water and nutrient transport to plant roots (Zahra *et al.,* 2025).

The drip fertigation + nanobubble treatment resulted in a 9.5% increase compared to the NPK treatment. Nutrient content in drip fertigation influences chlorophyll levels. Fe-EDTA in drip fertigation plays a role in plant metabolism and chlorophyll formation (Ahmed *et al.,* 2024). Furthermore, $MnSO_4$ plays a role in chlorophyll formation, photosynthesis, enzyme activation, and respiration (Khoshru *et al.,* 2023). The addition of nanobubble technology will support and enhance the function of each nutrient in increasing chlorophyll. Irrigation with nanobubble technology can increase chlorophyll content, iron, which is essential for photosynthesis (Zhao *et al.,* 2023). According to Kim *et al.* (2022), chlorophyll content and photosynthetic rate are benchmarks related to plant growth and production. Therefore, appropriate fertilizer application can increase chlorophyll content and nutrient uptake, optimizing plant production.

Chili yields and quality

Analysis of variance (ANOVA) results at the 5% level indicated an interaction between nutrient application and soil amendment on fruit weight per plant. Further testing revealed that the interaction of drip fertigation with nanobubbles and amendments yielded the best fruit weight per plant, at 299.18 g (Table 6).

The combination of nutrient solution + nanobubbles with ameliorant application further enhances nutrient availability in the root zone, significantly supporting fruit formation and weight gain. This is in line with research by Waramui *et al.* (2019) showed that ameliorant application resulted in an increase in fruit weight per plant of up to 44.9%. The ameliorant contains biochar, which can increase nutrient availability. This increase in availability due to biochar application can occur through direct supply via the biochar, nutrient retention capacity, and soil microbial dynamics (Adhikari *et al.,* 2024). Thus, ameliorant application can support the availability of nutrients needed by plants for optimal flower and fruit formation. The interaction between nutrient application and soil amendment on the number of fruits per plant. Based on further testing, the interaction of drip fertigation + nanobubble and ameliorants provided the best results in terms of fruit weight per plant, namely 59.25 fruits per plant (Table 7).

Based on the observation results, the fruit yields with quality A, C, and BS after analysis of variance at the 5% level did not show any interaction. However, there was an independent effect on the fruit yields with quality A, C, and good fruit quality (A+B) (Figure 3). Meanwhile, the fruit

Table 6: Effect of nutrients and soil conditioners application on fruit weight per plant

Fruit Weight/plant (g)			
Nutrients	**Soil conditioners**		
	Manure	**Bioameliorant**	**Ameliorant**
NPK	213.37^{aB}	208.71^{aAB}	176.53^{aA}
Drip fertigation	203.86^{aA}	236.01^{aAB}	257.72^{bB}
Drip fertigation+ Nanobubble	289.73^{bB}	196.28^{aA}	299.18^{bB}

The average value followed by the same letter is not significantly different according to Duncan's Test at a significance level of 0.05. Lowercase letters are read vertically, capital letters are read horizontally

Table 7: Effect of nutrient and soil conditioner application on the number of fruits per plant

Number of Fruits/Plants			
Nutrients	**Soil Conditioners**		
	Manure	**Bioameliorant**	**Ameliorant**
NPK	39.05^{aA}	37.28^{aA}	38.68^{aA}
Drip fertigation	36.80^{aAB}	36.03^{aA}	47.25^{abB}
Drip fertigation+ Nanobubble	54.10^{bB}	36.97^{aA}	59.25^{bB}

The average value followed by the same letter is not significantly different according to Duncan's Test at a significance level of 0.05. Lowercase letters are read vertically, capital letters are read horizontally.

Table 8: Effect of nutrient and soil conditioners application on fruit yield quality

Treatments	A (%)	C (%)	BS (%)	Good Quality (A+B) (%)
Nutrients				
NPK	6.78	30.60^b	5.84	63.55^a
Fertigasi drip	8.76	17.22^a	6.08	74.45^b
Fertigasi drip+Nanobubble	16.22	20.96^a	4.50	77.83^b
Soil conditioners				
Manure	5.03^a	27.97	4.69	67.11
Bioameliorant	16.01^c	20.25	7.39	73.81
Ameliorant	10.72^b	20.66	44.3	74.91

The average value followed by the same letter is not significantly different according to Duncan's Test at a significance level of 0.05.

yields with quality BS did not show any independent effect. In the fruit yields with quality A, there was an independent effect on the provision of soil conditioners in the form of bioameliorants, namely 16.01% of the total number of fruits (Table 8). According to the analysis results table, there was an independent effect on the nutritional treatment, namely NPK fertilizer, which gave higher results than other treatments on the fruit yields with quality C, namely 30.60% of the total number of fruits. Based on Table 8, the nutritional treatment in the form of drip fertigation + nanobubble gave higher results, but was not significantly different from drip fertigation.

The results of the analysis of variance at a 5% level showed that there was an interaction between the provision of nutrients and soil conditioners on the quality of fruit B. Based on the results of further tests, it was found that the interaction of drip fertigation and manure provided the best results on the quality of fruit B, namely 74.62% of the total fruit per plant (Table 9).

Guano in bioameliorants contains N, P, and K, which can improve soil fertility and increase nutrient levels in the soil (Możdżer, 2024). *Trichoderma* sp. biofertilizer can accelerate plant growth and increase crop yields (Zin & Badaluddin, 2020). The presence of PSB and NFB populations also supports plant growth, ultimately promoting the formation of high-quality flowers and fruit. NFB can assist in the process of fixing free nitrogen into ammonium or nitrate, which can be absorbed by plants (Zhang *et al.,* 2025).

The interaction between drip fertigation and manure on fruit quality showed the highest results compared to other treatments. The macro- and micronutrients in drip fertigation can improve fruit quality by meeting plant nutrient needs, enabling plants to grow well and produce optimal flower and fruit quality. Adding manure to the growing medium improves soil quality, thereby supporting nutrient absorption. Applying organic cow manure can improve the physical, chemical, and biological properties of the soil, including its role as a nutrient source for soil microbes and supporting plant growth (Denoncourt *et al.,* 2025).

Analysis of the relationship between chemical-biological properties of soil, yield and quality of chili yields

Based on the results of the Pearson correlation analysis (Figure 4), it is known that there is a significant relationship between several parameters of soil chemical-biological properties with growth characteristics on plant yield. One important result of this analysis shows that the NFB population (r=0.42), plant height (r=0.57), and stem diameter (r=0.76) have a significant positive correlation with fruit weight per plant. In addition, plant height (r=0.51), stem diameter (r=0.60), and chlorophyll (r=0.41) are significantly positively correlated with the number of fruits per plant. Meanwhile, pH is positively correlated with good fruit quality (A+B) (r=0.52), but negatively correlated with fruit quality C (r=-0.52).

Table 9: The effect of nutrients and soil conditioners application on fruit quality B

	Fruit quality B (%)		
Nutrients	Soil conditioners		
	Manure	Bioameliorant	Ameliorant
NPK	51.81^a	58.17^a	60.30^a
Fertigasi drip	74.62^b	61.12^a	71.41^{ab}
Fertigasi drip+Nanobubble	59.78^a	54.10^a	60.78^a

The average value followed by the same letter is not significantly different according to Duncan's Test at a significance level of 0.05. Lowercase letters are read vertically, capital letters are read horizontally

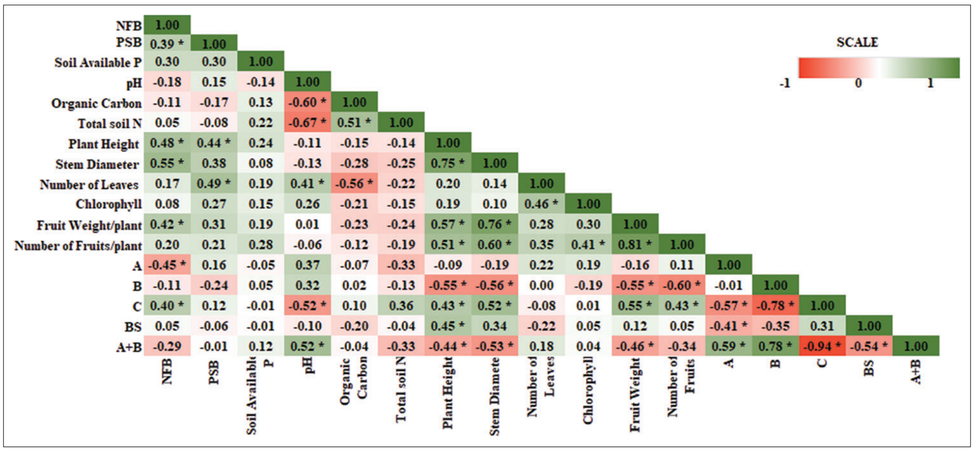
Table 10: Stepwise regression results of good fruit quality (A+B) as the dependent variable and all variables as the independent variables

Step	Parameter	Coef.	P-Value	R²
STEP 1	Intercept	-6.713	0.797	0.273
	pH	12.423	0.005	0.273
STEP 2	Intercept	-62.402	0.087	0.395
	pH	18.700	0.001	0.395
	Organic Carbon	5.565	0.038	0.395

Dependent variable=Good Fruit Quality (A+B)

The analysis continued by reducing the response variables that did not significantly influence red chili yields. To achieve this, stepwise regression analysis was used (Badri *et al.,* 2016). The dependent variable used in this analysis was good fruit quality (A+B) (Table 10). The results of this stepwise regression analysis will determine which variables will be used for path analysis.

Based on the results of stepwise regression, it is known that the variables that influence good fruit quality (A+B) as dependent variables are only pH and organic C. The independent variable pH is the first variable entered into the regression model and makes a significant contribution to the response variable, namely good fruit quality (A+B) with an



	NFB	PSB	Soil Availabl P	pH	Organic Carbon	Total soil N	Plant Height	Stem Diamete	Number of Leaves	Chlorophyll	Fruit Weight	Number of Fruits	A	B	C	BS	A+B
NFB	1.00																
PSB	0.39 *	1.00															
Soil Available P	0.30	0.30	1.00														
pH	-0.18	0.15	-0.14	1.00													
Organic Carbon	-0.11	-0.17	0.13	-0.60 *	1.00												
Total soil N	0.05	-0.08	0.22	-0.67 *	0.51 *	1.00											
Plant Height	0.48 *	0.44 *	0.24	-0.11	-0.15	-0.14	1.00										
Stem Diameter	0.55 *	0.38	0.08	-0.13	-0.28	-0.25	0.75 *	1.00									
Number of Leaves	0.17	0.49 *	0.19	0.41 *	-0.56 *	-0.22	0.20	0.14	1.00								
Chlorophyll	0.08	0.27	0.15	0.26	-0.21	-0.15	0.19	0.10	0.46 *	1.00							
Fruit Weight/plant	0.42 *	0.31	0.19	0.01	-0.23	-0.24	0.57 *	0.76 *	0.28	0.30	1.00						
Number of Fruits/plant	0.20	0.21	0.28	-0.06	-0.12	-0.19	0.51 *	0.60 *	0.35	0.41 *	0.81 *	1.00					
A	-0.45 *	0.16	-0.05	0.37	-0.07	-0.33	-0.09	-0.19	0.22	0.19	-0.16	0.11	1.00				
B	-0.11	-0.24	0.05	0.32	0.02	-0.13	-0.55 *	-0.56 *	0.00	-0.19	-0.55 *	-0.60 *	-0.01	1.00			
C	0.40 *	0.12	-0.01	-0.52 *	0.10	0.36	0.43 *	0.52 *	-0.08	0.01	0.55 *	0.43 *	-0.57 *	-0.78 *	1.00		
BS	0.05	-0.06	-0.01	-0.10	-0.20	-0.04	0.45 *	0.34	-0.22	0.05	0.12	0.05	-0.41 *	-0.35	0.31	1.00	
A+B	-0.29	-0.01	0.12	0.52 *	-0.04	-0.33	-0.44 *	-0.53 *	0.18	0.04	-0.46 *	-0.34	0.59 *	0.78 *	-0.94 *	-0.54 *	1.00

Figure 4: Correlation analysis matrix of soil chemical–biological properties, chili yield, and quality, where (*) indicates a statistically significant correlation

R2 value of 0.273, which means that soil pH affects good fruit quality (A+B) by 27.3%. Furthermore, the organic C variable is added to the model, increasing R2 to 0.395, which means that the combination of pH and organic C affects good fruit quality (A+B) by 39.5%. The variables pH and organic C of the stem have a positive relationship with good fruit quality (A+B). The regression equation obtained from the analysis results shows the relationship between good fruit quality (A+B) (Y) with two response variables, namely pH and organic C. The regression equation is as follows:

$$Y = -62.4017 + 18.7 * pH + 5.5652 * C - organic$$

The coefficient for pH is 18.7, meaning that for every one-unit increase in soil pH, the percentage of good quality (A+B) is estimated to increase by 18.7% of the total fruit. Furthermore, the coefficient for organic carbon is 5.57, meaning that for every 1% increase in soil organic carbon, the percentage of good quality (A+B) is estimated to increase by 5.57% of the total fruit.

Further analysis to better understand the results of the correlation and regression coefficients was conducted using path analysis. This analysis helps determine which variables have the most direct influence on the dependent variable and which variables are significant (Badri *et al.,* 2016). Therefore, path analysis was conducted to determine the direct effect of pH and organic carbon on good fruit quality (A+B) (Figure 5).

Based on the path analysis results, soil pH and organic carbon content had a direct influence on good fruit quality (grades A+B). Together, these two variables explained 92% of the variability in fruit quality, while the remaining 8% was influenced by factors outside the model (residual error=0.08). Of the two, organic carbon had the largest direct contribution, at 0.55, or 55%, followed by soil pH with a direct contribution of 0.18, or 18%. This indicates that organic carbon is the dominant factor in improving fruit quality.

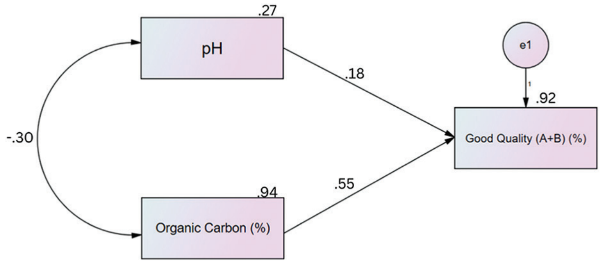


Figure 5: Relationship model between C-organic and pH on good fruit quality (A+B) with path coefficient values

In addition to their direct influence, both variables also have indirect effects. Organic carbon has an indirect influence on fruit quality through pH, with a path coefficient of –0.30×0.18=–0.054. Conversely, pH also has an indirect influence on fruit quality through organic carbon, with a path coefficient of –0.30×0.55=–0.165. Thus, the total effect of organic C—which is the sum of the direct and indirect effects—of 0.55+(–0.054)=0.496, remains the largest and most significant. Meanwhile, the total effect of pH is much smaller, namely 0.18+(–0.165)=0.015, indicating that although pH has a direct contribution, its negative indirect effect reduces its overall effectiveness in determining good fruit quality (A+B).

Conclusion

The interaction between nutrient and soil amendment treatments increased the available P (PSB) population, available P, fruit weight, and number per plant, as well as fruit quality. The interaction of drip fertigation + nanobubble and ameliorant treatments increased fruit weight and number per plant by 299.18 g/plant (39.77%) and 59.25 fruits/plant (34.1%), respectively, compared to the NPK and manure treatments. The NFB population, plant height, and stem diameter positively contributed to fruit weight per plant. Stem diameter, plant height, and chlorophyll content also positively affected fruit number. Furthermore, increasing soil pH correlated with improved fruit quality in categories A and B. The response variables pH and organic carbon directly affected fruit quality (A+B) by 39.5%. The application of nutrients using nanobubble technology has the potential to be implemented in red chili cultivation on soil enriched with soil conditioners.

Author contributions

Betty Natalie Fitriatin: Conceptualization, Investigation, Methodology, Writing - original draft. Alfira Zahra: Data curation, Formal analysis. Writing - review & editing. Nicky Oktav Fauziah: Investigation, Project administration. Moh Haris Imron S. Jaya: Validation, Visualization. Hanif Fakhrurroja: Funding acquisition, Software. Tien Turmuktini: Resources. Tualar Simarmata: Methodology, Supervision. All authors approved the final manuscript.

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