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Synergy of nanobubble drip-fertigation and soil bio-ameliorant on soil biochemical properties, growth, yield, and chili cash-crop quality in soil media

Nicky Oktav Fauziah[1,2*], Moh Haris Imron S Jaya[1], Alfira Zahra[3], Limbong Agatha Dita[3], Betty Natalie Fitriatin[4], Hanif Fakhrurroja[5], Tien Turmuktini[6], Tualar Simarmata[4]

[1] Doctoral Program of Agricultural Science, Faculty of Agriculture, Universitas Padjadjaran, Raya Bandung Sumedang Str. 21, Sumedang, 45363, Indonesia
[2] Department of Seed Technology, Politeknik Pembangunan Pertanian Yogyakarta-Magelang, Kusumanegara Str. 2, Yogyakarta, 55167, Indonesia
[3] Master Program of Agricultural Science, Faculty of Agriculture, Universitas Padjadjaran, Raya Bandung Sumedang Str. 21, Sumedang Regency, West Java 45363, Indonesia
[4] Department of Agricultural Science, Faculty of Agriculture, Universitas Padjadjaran, Raya Bandung Sumedang Str. 21, Sumedang, West Java 45363, Indonesia
[5] Research Center for Smart Mechatronics, National Research and Innovation Agency, Sangkuriang Str., Bandung, 40135, Indonesia
[6] Faculty of Agriculture, Universitas Winaya Mukti, Bandung-Sumedang Str. 29, Sumedang, 45362, Indonesia
* Corresponding author's e-mail: nicky14002@mail.unpad.ac.id

ABSTRACT

Nanobubble drip-fertigation (NDF) integrated with bio-ameliorant (BA), as an innovative and appropriate technology, sustainably restores soil health, enhances nutrient availability, and improves yield and quality of chili as a high-value cash crop at an efficient cost for small farmers. This study aimed to comprehensively assess the synergistic effects of nanobubble fertigation technology and bio-ameliorant on the growth, yield, quality, as well as grading of the chili cultivated in soil media within a simple plastic house structure. The experiment was set up as a strip plot consisted of nutrient delivery methods (conventional fertilizer (CF) = NPK 300 kg ha^{-1}, drip-fertigation (DP) = 1600 ppm, and NDF = oxygenated DF with 6.5 mg L^{-1} dissolve oxygen (DO) and soil amendments (conventional soil amendment (CS) = cow manure 20 t ha^{-1}, BA = bio-ameliorant 4 t ha^{-1}, A = ameliorant 4 t ha^{-1}) and provided three replications. Results revealed that oxygenated DF, combined with 6.5 mg L^{-1} DO and BA, significantly enhanced soil nutrient availability and microbial activity. This treatment notably improved chili fruit quality, achieving a 79.33% Grade A rating, as well as increased fruit number and weight. Correlation and Principal Component analyses confirmed strong relationships between soil biochemical parameters and yield components, while path analysis identified fruit number as the primary determinant of total yield. The findings offer a sustainable and efficient alternative to conventional fertilization, providing practical insights for smallholder farmers aiming to optimize chili productivity and quality through integrated soil and nutrient management strategies.

Keywords: plastic house, nutrient solution, nutrient use efficiency, ameliorant, drip irrigation, soil amendment.

INTRODUCTION

Nanobubble drip-fertigation and soil bio-ameliorant, as innovative and appropriate technologies, are increasingly adopted by smallholder farmers in Indonesia to enhance chili crop productivity and quality. Chili, a key high-value horticultural cash crop, holds significant economic importance in Asia, particularly in Indonesia, where keywords such as innovation, sustainability, productivity, and quality are gaining growing attention. The approach is achieved through the use of soil media, which is relatively inexpensive and easily accessible, contains millions of organisms, as well as regulates carbon, nutrient, and hydrological cycles (FAO, 2022). One such technology is the simultaneous application of water and nutrients, known as drip-fertigation technology, which aims to improve the efficiency of water and nutrient use, minimize environmental impact, as well as improve crop yields (Khan and Sarwar, 2023; Paramesha et al., 2022). A new approach utilizes nanobubble fertigation technology, which enhances oxygen availability and nutrient uptake, in combination with enriched ameliorants to improve and restore soil fertility and health (Zahra et al., 2025; Zhou et al., 2022). This integrated system is a promising strategy with the potential to significantly enhance output and quality, making chili farming more productive and sustainable (Hassan et al., 2023).

Nanobubble drip fertigation integrates nanobubble technology with drip irrigation to enhance chili cultivation. Ultrafine gas bubbles (<200 nm) increase dissolved oxygen and nutrient uptake efficiency in the root zone, improving plant growth and yield (Bian et al., 2025; Lei et al., 2023). This system ensures precise delivery of oxygen-enriched nutrients, stimulates microbial activity, and reduces fertilizer loss. Studies report yield increases of 20–35% and plant height improvements of 18–25% compared to conventional fertigation (Lei et al., 2024). By enhancing soil aeration and nutrient use efficiency while minimizing water and energy inputs, nanobubble drip fertigation supports sustainable, high-efficiency production for smallholder farmers.

Soil amendments play a crucial role in restoring soil health and enhancing nutrient availability, both of which are essential for improving crop productivity. Traditionally, farmers rely heavily on composted manure, particularly cow dung, due to its wide availability and ability to add organic matter as well as improve soil fertility. However, conventional manures have several limitations, including low nutrient content, inconsistent quality, and the requirement for high application rates—typically around 20 t ha^{-1} or 141 g per plant—to achieve measurable effects. To overcome these challenges, bio-ameliorants have emerged as a promising alternative. Enriched bio-ameliorants, when combined with nutrient solutions and biofertilizers, can provide a more balanced supply of essential nutrients, stimulate beneficial soil microbial activity, and enhance plant growth. Recent findings indicate that the integrated application of an ameliorant, a nutrient solution, and 6 kg ha^{-1} biofertilizer significantly improved the fruit diameter and length of red chili (Fitriatin et al., 2024), underscoring the synergistic potential of bio-ameliorant-based technologies for high-value cash crops.

To address the limitations of conventional amendments, soil ameliorants, such as compost, charcoal, guano, and dolomite are increasingly applied to improve soil fertility and structure more effectively. Biochar, for instance, enhances soil quality by increasing nutrient bioavailability and stimulating beneficial microbial activity (Kabir et al., 2023; Mensah et al., 2025). Guano, particularly in tropical sandy soils, mineralizes rapidly and acts similarly to mineral fertilizers, providing a fast-acting nitrogen source for plants (Dimande et al., 2023). Beyond these traditional materials, a more advanced approach involves the use of bio-ameliorants, which are soil ameliorants enriched with beneficial biological agents or biofertilizers. Bio-ameliorants not only improve nutrient availability, but also suppress soil-borne diseases, enhance soil biochemical processes, and stimulate plant growth (Fitriatin et al., 2021; Simarmata et al., 2019). By integrating organic matter with functional microbes, bio-ameliorants provide a synergistic and sustainable solution for rehabilitating degraded soils, improving crop productivity, and reducing reliance on chemical fertilizers. As such, bio-ameliorants represent a transformative innovation in sustainable soil management, particularly for high-value cash crops like chili.

Previous studies have rarely investigated the synergistic integration of advanced fertigation technologies with soil bio-ameliorants and their combined influence on growth media properties and chili fruit quality. This study aims to comprehensively evaluate the synergistic effects of nanobubble fertigation technology and soil bio-ameliorants on media properties, nutrient availability, plant health, yield performance, and chili quality. It further examines the correlations among soil biochemical parameters, plant growth dynamics, productivity, and fruit characteristics. Additionally, a predictive model is developed to describe the relationship between high-quality chili yield and its determining factors. The findings are expected to provide a sustainable and practical cultivation strategy for smallholder chili farmers, offering a breakthrough approach to improving productivity and quality in soil-based systems. The relevance is underscored by the role of chili as one of Indonesia's most important cash-crop vegetables.

METHODS

Location

The experiment was conducted in a simple plastic house with a bamboo frame and a UV plastic roof, located at Bale Tatanen, Faculty of Agriculture, Universitas Padjadjaran, Jatinangor (coordinates: 6°55'32.4"S, 107°46'46.6"E), at an altitude of approximately 725 meters above sea level. The site is characterized by an average minimum temperature of 20–22 °C, a maximum temperature of 29–31 °C, and average solar radiation of 4.5–5.0 kWh/m²/day. The plastic house was equipped with nine soil beds, each measuring 6 m in length and 1 m in width, and spaced 50 cm apart to facilitate crop management. A drip fertigation system was installed in each bed, equipped with emitters directly placed into the soil medium inside polybags to deliver water and nutrients efficiently.

The growing medium consisted of 10 kg of upper Inceptisol soil per polybag. The Inceptisol was collected from Jatinangor, West Java. Laboratory analyses conducted at the Soil Chemistry and Plant Nutrition Laboratory, Department of Soil Science and Land Resources, Faculty of Agriculture, Universitas Padjadjaran (2024), was characterized by an acidic pH (pH 5.0–5.5), specifically total nitrogen was 0.304% and exchangeable potassium was 0.55 me 100 g⁻1, both were categorized as moderate, and available phosphorus was 10.8 ppm categorized as low based on standard soil fertility classifications, which commonly limits crop productivity. These results indicate limited organic matter and base nutrients, but a moderate cation retention capacity.

The experimental materials included the Inceptisol soil, nutrient stock solutions A and B, and red chili (*Capsicum annuum*) seeds of the Tanjung variety. Red chili was selected for its higher market value compared to curly chili over the past two years (PIHPS, 2023). Consumers preferred the Tanjung variety for its large fruit size and bright red color. Pest and disease management employed insecticides containing profenofos, deltamethrin, and iafentiuron, as well as fungicides containing difenoconazole, chlorothalonil, and propineb. Additional reagents and culture media were used for biological and chemical analyses of soil samples.

Research design and procedure

The experimental design used was a strip plot design with nine treatments (three nutrient delivery methods × three soil amendments), replicated three times, resulting in a total of 81 experimental units (Figure 1).

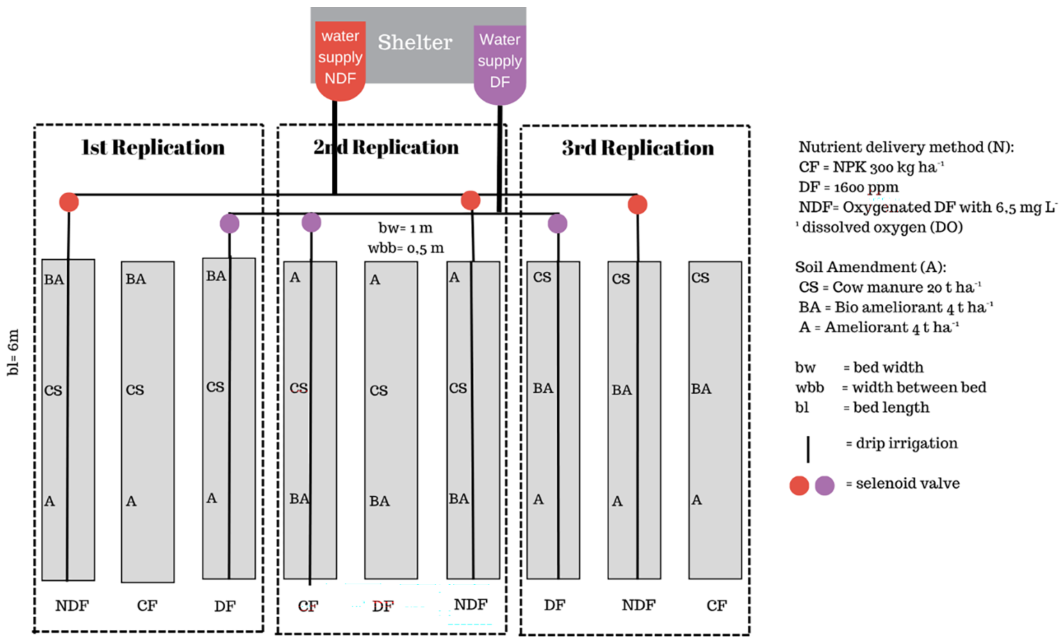

Figure 1. Experimental layout showing three replications combining nutrient delivery methods (CF, DF, NDF) and soil amendments (CS, BA, A) under a drip irrigation system

Soil amendment

The soil amendments used in this study included cow manure, an ameliorant, and a bio-ameliorant. Cow manure was selected as a representative of the conventional soil amendment commonly applied by chili farmers at a relatively high rate of 20 t ha [1]. In contrast, the ameliorant and bio-ameliorant were applied at a lower rate of 4 t ha^{-1}. The ameliorant consisted of a mixture of compost (50%), coconut shell biochar (30%), dolomite (10%), and guano (10%). The bio-ameliorant was prepared by enriching the ameliorant with 6 kg ha^{-1} of biofertilizer containing *Trichoderma* spp., nitrogen-fixing bacteria (NFB), and phosphate-solubilizing bacteria (PSB). The bio-ameliorant was found to enhance both the fruit diameter and length of red chili (Fitriatin, Dupa, et al., 2024).

The bacterial diversity of the soil and bio-ameliorant used in this study was analyzed at the Soil Biology Laboratory, Department of Soil Science and Land Resources, Faculty of Agriculture, Universitas Padjadjaran, in 2024. The results showed that the population of PSB in the soil was 1×10^6 CFU mL^{-1}, and 3×10^6 CFU mL^{-1} in the bio ameliorant. Interestingly, the NFB population was not detected in the soil (0 CFU mL^{-1}) but was present in the bio ameliorant, reaching 8.5×10^7 CFU mL^{-1}. Additionally, the total bacterial population was 10.88×10^9 CFU mL^{-1} in the soil and 12.36×10^9 CFU mL^{-1} in the bio ameliorant.

Nanobubble drip-fertigation technology

The nanobubble system was assembled by installing a nanobubble pump into a 500-liter water tank. Before activation, water and nutrients were mixed in the tank, with the system scheduled to operate between 07:00 and 07:30. Nutrient solutions A and B were combined according to the required concentrations for each stage of plant growth: 800 ppm during weeks 1–2 after planting (WAP), 1200 ppm during weeks 3–4 WAP, and 1600 ppm from week 5 until harvest. Nutrient solution A contains macronutrients consisting of $Ca(NO_3)_2$, KNO_3, and Fe-EDTA. $Ca(NO_3)_2$, while nutrient solution B contains various macro- and micronutrients, such as KH_2PO_4, $(NH_4)SO_4$, K_2SO_4 (ZK), $MgSO_4.7H_2O$, $CuSO_4$, $ZnSO_4$, H_3BO_3, MNSO, Mo-NH_4.

The nanobubble machine operates by utilizing atmospheric oxygen. Once drawn into the pump, the oxygen is compressed and mixed with water, then dispersed into nanobubbles by the nanobubble generator. This process produces fantastic bubbles (with diameters less than 200 nm), enhancing the solubility of oxygen in water. The machine operates for 30 minutes, during which the dissolved oxygen (DO) concentration in the water increases from approximately 5 mgL^{-1} to 6.5 mgL^{-1}. Following application, the dissolved oxygen content in the soil is measured using a soil DO sensor once the oxygenated nutrient solution has infiltrated the soil (Figure 2).

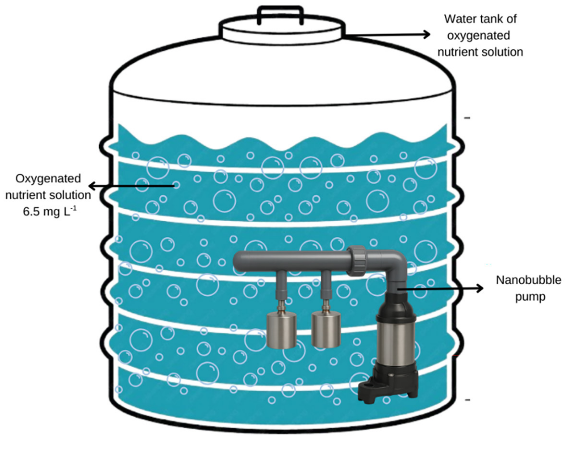

Figure 2. Visualization of the oxygenation process using a nanobubble pump inside a 500 L nutrient solution tank

The nanobubble pump utilized a two-chamber swirling-flow nozzle driven by a variable-frequency centrifugal pump to generate stable oxygen and air nanobubbles continuously via hydrodynamic cavitation. With liquid flow rates of 14–38 L min^{-1} and a fixed gas flow of 1 L min^{-1}, the system produced bubbles smaller than 200 nm and zeta potentials around −20 mV (Alam et al., 2022).

The dissolved oxygen (DO) concentration in the nanobubble fertigation (NDF) system was maintained at 6.5 mg/L to ensure its practicality and operational efficiency under smallholder farming conditions. Increasing the DO level from 5 mg L^{-1} to 6.5 mg L^{-1} in 500 L of water requires approximately 30 minutes, whereas elevating it to 9 mg L^{-1} would take around 1.5 hours. Such an extended aeration duration is impractical for field implementation, particularly for small-scale farmers with limited technical resources. This operational constraint formed the basis for the decision to set the DO level at 6.5 mg L^{-1}, which represents a balance between oxygen enrichment and field applicability.

Recent studies have demonstrated the effectiveness of nanobubble technology in the agricultural sector. For example, the irrigation using oxygen nanobubbles has been shown to improve tomato seed germination by 10%, enhance plant growth by 30–50%, and increase leaf peroxidase activity by 500–1000%, potentially supporting cell proliferation and overall growth (Xue et al., 2023). Furthermore, nanobubble oxygenation irrigation has been found to improve phosphorus availability in soil as well as increase maize production by affecting the quantity and structure of core microbial communities (Bian et al., 2025).

Crop establishment and maintenance

Red chili seeds were soaked in water for 5 minutes, and only the seeds that sank to the bottom were selected for use. The seeds were sown in a seedling medium composed of soil, compost, and rice husk charcoal at a ratio of 1:1:2. During the first week, the seedling trays were placed in a shaded area, and then moved to a seedling screen house once germination occurred. Transplanting was carried out 28 days after sowing (DAS). The planting media was prepared through land sanitation, mulch installation, and the use of Inceptisol soil that had been air-dried for one week. The soil was mixed with either 20 t ha^{-1} (A1), 4 t ha^{-1} of bio-ameliorant (A2), or 4 t ha^{-1} of ameliorant (A3) and then placed into 35 × 35 cm polybags, which were subsequently covered with silver-black plastic mulch to reduce evaporation.

Seedlings with 7–8 leaves were transplanted in the afternoon into polybags filled with the prepared planting medium, with a spacing of 60 × 70 cm. Crop maintenance included irrigation combined with nutrient solution application, replanting, weeding, hilling-up, pruning of shoots, staking, as well as pest and disease control. The nutrient application was carried out using urea, SP-36, and KCl fertilizers at a dosage of 300 $kg.ha^{-1}$ each (Piay et al., 2010). The nutrient solution concentration started at 500 ppm during the nursery stage, increased to 800 ppm at 1–2 weeks after planting (WAP), 1200 ppm at 3–4 WAP, and then remained at 1600 ppm from 5 WAP until harvest. Daily observations were conducted using a SOC sensor, while vegetative parameters were observed during the late vegetative stage when the plants began to flower at 6 weeks after planting (WAP). Harvesting of red chili began 58 days after transplanting (DAT), targeting physiologically mature fruits characterized by a glossy red color. Harvesting was carried out every three days for a total of twelve harvests.

Observed response

The data collected were based on observations, with the following details:

a) soil biochemical properties: exchangeable potassium, available phosphorus, soil oxygen content (SOC), and phosphate-solubilizing (PSB) bacteria.
b) yield character: fruit length, fruit diameter, number of fruits per plant, fruit weight per plant, fruit weight per plant.
c) yield quality: the quality grading was classified based on CODEX STAN 307-2011 and Indonesian National Standard (SNI) for Chili (SNI 01-4483-1998), classified as Grade A, B, and C (Table 1), which were assessed during the harvest.

Statistical analysis

The acquired data was processed and statistically analyzed with R-Studio 4.4.1 software. Initially, the Shapiro-Wilk test was used to determine whether the data were normally distributed. The data were analyzed using ANOVA, followed by Duncan's test for significant differences. Mean separation was determined using the Multiple Range Test (DMRT) at a significance level of 5%.

Growth and yield components were further analyzed using Pearson correlation analysis to determine the relationships between variables

Table 1. Grading fruit quality guidance

Grade	Fruit Length (cm)	Impurity level (%)	Color	Damage and decay (%)	Appearance	Notes
Grade A	8 < 12	1	Bright red	0	Smooth, uniform, free from defects	Premium quality, free of defects, export-grade
Grade B	4 < 8	2	Red	1	Minor defects allowed (e.g., small scars)	Suitable for local markets
Grade C	≤ 4	3	Red	2	Irregular shape or mild discoloration	Often used for processing

(Budiarto et al., 2024). Additionally, principal component analysis (PCA) biplot analysis was performed to identify relationship patterns among variables as well as to visually and integratively assess the contribution of each parameter to the variation across treatments.

RESULTS AND DISCUSSION

Soil biochemical properties

The synergistic effect of the treatments significantly influenced key soil biochemical properties, including exchangeable potassium (Table 2), soil oxygen concentration (Table 3), the population of phosphate-solubilizing bacteria (PSB) (Table 4), and available phosphorus content (Table 5), demonstrating enhanced nutrient availability and overall soil biochemical functionality.

The NDFA treatment (Oxygenated DF with 6.5 mg L^{-1} dissolved oxygen + 4 t ha^{-1} ameliorant) showed no significant difference compared to the NDFBA treatment (Oxygenated DF with 6.5 mg L^{-1} dissolved oxygen + 4 t ha^{-1} bio-ameliorant), and the DFCS treatment (nutrient solution at 1600 ppm + 20 t ha^{-1} cow manure). This result suggests that the type of soil amendment significantly influences exchangeable potassium, meaning that 4 t ha^{-1} of ameliorant can provide higher results than 20 t ha^{-1} of cow manure. Similarly, different nutrient delivery methods, nutrient solution application, and oxygenated fertigation have a significant influence on exchangeable potassium availability compared to conventional NPK fertilization. This result suggests the positive impact of nutrient inputs, particularly those rich in potassium or capable of stimulating microbial activity that enhances K availability (Wihardjaka et al., 2022). It demonstrates that the right combination of amendment and nutrition can synergistically improve K status in soil.

A similar pattern was observed in the soil oxygen content (SOC) parameter, where the NDFA treatment (Oxygenated DF with 6.5 mg L^{-1} dissolved oxygen + 4 t ha^{-1} ameliorant) showed no significant difference compared to all other treatments, except for DFA (nutrient solution at 1600 ppm + 4 t ha^{-1} ameliorant) and CFA (NPK at 300 kg ha^{-1} + 4 t ha^{-1} ameliorant). This result suggests that SOC was not significantly influenced by variations in dissolved oxygen (DO) levels in the

Table 2. Synergistic effect of nutrient delivery method and soil amendment on exchangeable potassium (me 100 g-1)

Nutrient delivery method (N)	Soil Amendment (A)		
	CS = Cow manure 20 t ha^{-1}	BA = Bio-ameliorant 4 t ha^{-1}	A = Ameliorant 4 t ha^{-1}
CF = NPK 300 kg ha^{-1}	3.26 b A	1.02 b B	1.09 b B
DF = 1600 ppm (NS)	**4.90 a A**	3.17 a B	2.70 a B
NDF = Oxygenated DF with 6,5 mg L^{-1} DO	3.33 b A	**3.73 a A**	**3.19 a A**

Note: numbers followed by the same letter are not significantly different according to the Duncan-DMRT follow-up test at a 5% significance level. Lowercase letters are read vertically, comparing the two nutritional delivery methods (N) within the same soil amendment (A). Uppercase letters are read horizontally, comparing the two soil amendments (A) within the same nutritional delivery method (N).

Table 3. Synergistic effect of nutrient delivery method and soil amendment on soil oxygen content (SOC)

Nutrient delivery method (N)	Soil Amendment (A)		
	CS = Cow manure 20 t ha^{-1}	BA = Bio-ameliorant 4 t ha^{-1}	A = Ameliorant 4 t ha^{-1}
CF = NPK 300 kg ha^{-1}	**20.91 a A**	**20.8 a A**	20.61 b A
DF = Nutrient solution 1600 ppm (NS)	**20.79 a A**	**20.70 a A**	20.68 ab A
NDF = Oxygenated DF with 6,5 mg L^{-1} DO	**20.71 a A**	**20.87 a A**	**20.81 a A**

Note: numbers followed by the same letter are not significantly different according to the Duncan-DMRT follow-up test at a 5% significance level. Lowercase letters are read vertically, comparing the two nutritional delivery methods (N) within the same soil amendment (A). Uppercase letters are read horizontally, comparing the two soil amendments (A) within the same nutritional delivery method (N).

Table 4. Synergistic effect of nutrient delivery method and soil amendment on phosphate-solubilizing bacteria (PSB) population (10-7)

Nutritional delivery methods (N), N	Soil amendment (A)		
	CS = Cow manure 20 t ha^{-1}	BA = Bio-ameliorant 4 t ha^{-1}	A = Ameliorant 4 t ha^{-1}
CF = NPK 300 kg ha^{-1}	**45.83 a A**	**40.00 a A**	56.33 b A
DF = Nutrient solution 1600 ppm (NS)	**89.83 a A**	62.50 a AB	46.50 b B
NDF = Oxygenated DF with 6,5 mg L^{-1} DO	64.00 a B	61.67 a B	**133,.00 a A**

Note: Numbers followed by the same letter are not significantly different according to the Duncan-DMRT follow-up test at a 5% significance level. Lowercase letters are read vertically, comparing the two nutritional delivery methods (N) within the same soil amendment (A). Uppercase letters are read horizontally, comparing the two soil amendments (A) within the same nutritional delivery method (N).

Table 5. Synergistic effect of nutrient delivery method and soil amendment on available phosphorus (ppm)

Nutrient delivery method (N)	Soil Amendment (A)		
	CS = Cow manure 20 t ha^{-1}	BA = Bio-ameliorant 4 t ha^{-1}	A = Ameliorant 4 t ha^{-1}
CF = NPK 300 kg ha^{-1}	**64.92 a A**	29.50 b B	20.19 c B
DF = Nutrient solution 1600 ppm (NS)	51.21 b A	19.50 b B	42.28 b A
NDF = Oxygenated DF with 6,5 mg L^{-1} DO	16.91 c C	44.41 a B	**79.32 a A**

Note: Numbers followed by the same letter are not significantly different according to the Duncan-DMRT follow-up test at a 5% significance level. Lowercase letters are read vertically, comparing the two Nutritional Delivery Methods (N) within the same Soil Amendment (A). Uppercase letters are read horizontally, comparing the two Soil Amendments (A) within the same Nutritional Delivery Method (N).

nutrient solution or by different soil amendment types, likely because the DO concentration was only increased to 6.5 mgL⁻1. Before applying the nutrient solution, the nanobubble generator was activated to increase the dissolved oxygen (DO) in the water from 5 mgL^{-1} to approximately 6.5 mgL^{-1}. A DO concentration of 9 mg/L has been reported to enhance SOC, water use efficiency, soil environment, and tomato plant growth (Ouyang et al., 2021).

Another study showed that 15 mg L^{-1} was recommended for seedling and production seed of tomato crops in a greenhouse (Zhang et al., 2024). The lack of difference in soil DO after the application of the nanobubble-treated solution may be attributed to the insufficient increase in DO concentration. Ideally, the DO level should be raised to 9–15 mg/L to enhance SOC effectively.

The synergistic effects of the NDFA treatment (Oxygenated DF with 6.5 mg L^{-1} dissolved oxygen + ameliorant at 4 t ha^{-1}) did not show a significant difference compared to the DFCS treatment (nutrient solution at 1600 ppm + cow manure at 20 t ha^{-1}), the CFCS treatment (NPK at 300 kg ha^{-1} + cow manure at 20 t ha^{-1}), and the CFBA treatment (NPK at 300 kg ha^{-1} + bio-ameliorant at 4 t ha^{-1}) in terms of PSB population parameters. This result indicates that the PSB population is not affected by the type of soil amendment used. However, the application of ameliorant and bio-ameliorant at 4 t ha^{-1} produced similar results to the application of cow manure at 20 t ha^{-1}, suggesting that the use of ameliorants can reduce the excessive reliance on high doses of cow manure.

This suggests that certain combinations of organic amendments and nutrient treatments can selectively enhance the abundance of functional microbes, such as PSB. Organic inputs increase soil organic carbon, which in turn supports the growth and activity of PSB. For instance, the application of organic fertilizers has been shown to boost the population of PSB by providing a rich source of carbon, which is essential for their metabolic activities (Kumar and Rai, 2020; Sun et al., 2021). Similarly, (Ambarita et al., 2025) reported that the combined application of biofertilizer and organic ameliorant significantly increased the phosphate-solubilizing bacteria (PSB) populations across all fertilizer levels, indicating a synergistic effect that enhances microbial habitat and nutrient availability.

Similar to other parameters, the synergistic effect of the NDFA treatment (oxygenated N_2 with 6.5 mg L^{-1} dissolved oxygen + ameliorant 4 t ha^{-1}) and CFCS treatment (NPK at 300 kg ha^{-1} + cow manure 20 t ha^{-1}) showed no significant difference in available phosphorus levels. This result suggests that high doses of conventional fertilizers and soil amendments can be effectively replaced with alternative strategies, such as oxygenated fertigation combined with organic amendments. These methods not only maintain phosphorus availability, but also offer additional benefits, such as improved soil health and reduced environmental impact (Islam et al., 2026; Mamun et al., 2022). Therefore, the NDFA treatment could be a viable alternative to the CFCS treatment for maintaining soil phosphorus levels, with no significant differences in efficacy.

Chili yield and quality

On the basis of on the synergistic effect of the treatments, it was found that all treatments had a significant impact on the number of fruits per plant (Table 6) and the weight of each fruit (Table 7). The NDFCS treatment (Oxygenated DF with 6.5 mg L^{-1} DO + cow manure 20 t ha^{-1}), NDFA (Oxygenated DF with 6,5 mg L^{-1} DO + ameliorant 4 t ha^{-1}), DFA treatment (Nutrient solution 1600 ppm + ameliorant 4 t ha^{-1}), and CFCS treatment (NPK 300 kg ha^{-1}+ cow manure 20 t ha^{-1}) give the same results of number of fruits per plant.

This result suggests that a well-matched soil amendment and nutrient management strategy can simultaneously optimize both yield and quality traits. It could be caused by the fact that the nutrient solution includes a complete set of important elements (including macro- and micronutrients) in readily available forms, allowing plants to achieve their nutritional requirements more efficiently (Fitriatin, Ghiffari, et al., 2024). These results underscore the importance of integrating suitable soil amendments with targeted nutrition programs to achieve specific production objectives in chili cultivation. The DFBA treatment (nutrient solution 1600 ppm + bio-ameliorant 4 t ha^{-1}) yielded the best results in terms of weight per fruit compared with other treatments. This result shows that the use of nutrient solutions combined with bio-ameliorant can increase the number of plant fruits.

In contrast to other yield parameters, the soil amendment and nutrient delivery method

Table 6. Synergistic effect of nutrient delivery method and soil amendment on the number of fruits per plant

Nutrient Delivery Method (N)	Soil Amendment (A)		
	CS = Cow manure 20 t ha^{-1}	BA = Bio-ameliorant 4 t ha^{-1}	A = Ameliorant 4 t ha^{-1}
CF = NPK 300 kg ha^{-1}	**13.33 a A**	9.33 a B	7.67 c B
DF = Nutrient solution 1600 ppm (NS)	**12.45 a A**	8.55 a B	12.00 b A
NDF = Oxygenated DF with 6.5 mg L^{-1} DO	**12.55 a A**	9.44 a B	**14.89 a A**

Note: numbers followed by the same letter are not significantly different according to the Duncan-DMRT follow-up test at a 5% significance level. Lowercase letters are read vertically, comparing the two nutritional delivery methods (N) within the same soil amendment (A). Uppercase letters are read horizontally, comparing the two soil amendments (A) within the same nutritional delivery method (N).

Table 7. Synergistic effect of nutrient delivery method and soil amendment on weight per fruit (g)

Nutritional delivery methods (N	Soil amendment (A)		
	CS = Cow manure 20 t ha^{-1}	BA = Bio-ameliorant 4 t ha^{-1}	A = Ameliorant 4 t ha^{-1}
CF = NPK 300 kg ha^{-1}	6.31 a B	6.14 b C	6.64 b A
DF = Nutrient solution 1600 ppm (NS)	6.08 b C	**7.23 a A**	7.09 a B
NDF = Oxygenated DF with 6.5 mg L^{-1} DO	5.97 c A	5.75 c B	4.52 c C

Note: numbers followed by the same letter are not significantly different according to the Duncan-DMRT follow-up test at a 5% significance level. Lowercase letters are read vertically, comparing the two nutritional delivery methods (N) within the same soil amendment (A). Uppercase letters are read horizontally, comparing the two soil amendments (A) within the same nutritional delivery method (N).

treatment showed independent results only in the yield weight per plant and fruit length treatments. The results of the analysis showed that the treatment of BA (bio-ameliorant 4 t ha^{-1}) and the treatment of DF (NS 1600 ppm) independently had a significant effect on fruit length (Table 8). The use of biofertilizers incorporated into ameliorants and nutrient solutions has been reported to improve chili fruit traits, such as fruit length (Fitriatin et al., 2024). The present findings complement previous studies by demonstrating that bio-ameliorants can also enhance individual fruit weight in chili.

Meanwhile, in the yield weight parameters per plant, the treatment of A1 (cow manure 4 t ha^{-1}) and N1 (NPK 300 kg ha^{-1}) independently gave significant results compared to other treatments. This result indicates that conventional technology receives greater weight than other treatments, but not necessarily in other parameters that indicate the quality of the results. In addition to yield, the treatments also significantly influenced the quality of chili fruits (Table 9). The interaction analysis between soil amendment (A) and nutrition (N) treatments had a significant effect on Grades A, B, and C. The NDFBA treatment (Oxygenated DF with 6.5 mg L^{-1} dissolved oxygen + ameliorant 4 t ha^{-1}) yielded the best results for Grade A.

The superior performance of the nanobubble nutrient solution (N3) in producing higher Grade A fruits aligns with findings that nanobubbles enhance nutrient delivery efficiency by improving oxygen availability at the root zone, promoting better root metabolism and fruit set quality (Malahlela et al., 2024). Nanobubbles are known to enhance the solubility of oxygen and nutrients in water, resulting in more vigorous and healthy plants. Significant interaction effects for Grade A and Grade BS fruits imply that soil amendments and nutrition technology synergistically affect the production of premium fruits. The synergistic effect of NDFBA treatment (Oxygenated DF with 6.5 mg L^{-1} dissolved oxygen + ameliorant 4 t ha^{-1}) produced the Grade A fruits (79.33%), indicating that physical improvements in soil structure (ameliorant) combined with efficient nutrient delivery (nanobubble technology) can substantially boost fruit quality. The higher incidence of the Grade A fruits in A2 (bio-ameliorant) can be attributed to improved soil texture and increased microbial activity, which in turn influence fruit development and quality (Cui et al., 2023; Liu et al., 2023).

In contrast to grade A, the NDFCS treatment (Oxygenated DF with 6.5 mg L^{-1} DO + Cow manure 20 t ha^{-1}) gave the same results as the DFA treatment (NS 1600 ppm + Cow manure 20 t ha^{-1}), DFBA treatment (NS 1600 ppm + bio-ameliorant t ha^{-1}), and CFA (NPK 300 kg ha^{-1} + ameliorant 4 t ha^{-1}) on Grade B parameters (Table 10). This

Table 8. The main effect of the nutrient delivery method and soil amendment on yield weight per plant (g) and fruit length (cm)

Treatment	Yield weight per plant	Fruit length
	(g)	(cm)
Soil amendment (A)		
CS = Cow manure 20 t ha^{-1}	**88.68 a**	10.55 b
BA = Bio-ameliorant 4 t ha^{-1}	51.84 c	**10.68 a**
A = Ameliorant 4 t ha^{-1}	82.63 b	10.36 c
Probability	**	**
P-value	0,000	0,374
Nutrient delivery methods (N)		
CF = NPK 300 kg ha^{-1}	**80.67 a**	10.45 c
DF = Nutrient solution 1600 ppm (NS)	68.48 c	**10.59 a**
NDF = Oxygenated DF with 6,5 mg L^{-1} DO	74.00 b	10.54 b
Probability	**	**
P-value	0.000	0.009
Soil amendment (A) x nutrient delivery method (N)		
Probability	ns	ns
P-value	1.000	1.000

Note: numbers followed by the same letter are not significantly different according to the Duncan-DMRT follow-up test at a 5% significance level.

Table 9. Synergistic effect of nutrient delivery method and soil amendment on the Grade A quality of chili (%)

Nutritional delivery methods (N)	Soil amendment (A)		
	CS = Cow manure 20 t ha^{-1}	BA = Bio-ameliorant 4 t ha^{-1}	A = Ameliorant 4 t ha^{-1}
CF = NPK 300 kg ha^{-1}	67.08 a B (0.00%)	74.41 b A (7.33%)	55.68 c C (-11.4%)
DF = Nutrient solution 1600 ppm (NS)	66.33 b C (-0.75%)	74.43 b A (7.35%)	73.38 a B (6.3%)
NDF = Oxygenated DF with 6.5 mg L^{-1} DO	59.81 c C (-7.27%)	**79.33 a** **A** **(12.25%)**	69.08 b B (2.00%)

Note: numbers followed by the same letter are not significantly different according to the Duncan-DMRT follow-up test at a 5% significance level. Lowercase letters are read vertically, comparing the two nutritional delivery methods (N) within the same soil amendment (A). Uppercase letters are read horizontally, comparing the two soil amendments (A) within the same nutritional delivery method (N).

Table 10. Synergistic effect of nutrient delivery method and soil amendment on the Grade B quality of chili (%)

Nutritional delivery methods (N)	Soil amendment (A)		
	A1 (Cow manure 20 t ha^{-1})	A2 (Bio-ameliorant 4 t ha^{-1})	A3 (Ameliorant 4 t ha^{-1})
CF = NPK 300 kg ha^{-1}	23.42 a B	22.56 ab B	**35.99 a** **A**
N2 Nutrient solution 1600 ppm (NS)	**24.25 a** **A**	**24.47 a** **A**	24.60 b A
N3= Oxygenated DF with 6.5 mg L^{-1} DO	**27.17 a** **A**	13.33 b B	29.40 ab A

Note: numbers followed by the same letter are not significantly different according to the Duncan-DMRT follow-up test at a 5% significance level. Lowercase letters are read vertically, comparing the two nutritional delivery methods (N) within the same soil amendment (A). Uppercase letters are read horizontally, comparing the two soil amendments (A) within the same nutritional delivery method (N).

suggests that the quantity of the results does not reflect the quality. The combination of optimal fertilization and soil amendments generally leads to improved fruit quality (Islam et al., 2026; Zhang et al., 2023). However, further specific studies are needed to determine their effects on the Grade B quality of chili conclusively

In contrast to grade B, the treatment of CFCS (NPK 300 kg ha^{-1} + cow manure 20 t ha^{-1}), DFCS (NS 1600 ppm + cow manure 20 t ha^{-1}), and NDF-CS (Oxygenated DF with 6.5 mg L^{-1} DO + cow manure 20 t ha^{-1}) gave the same results at grade C (Table 11). This result shows that the use of manure yields poor results in terms of quality, with grade C being higher than other treatments.

Each amendment has distinct benefits and potential risks. Cow manure is highly effective in enhancing soil nutrients and crop yield,

Table 11. Synergistic effect of nutrient delivery method and soil amendment on Grade C quality of chili (%)

Nutritional delivery methods (N)	Soil amendment (A)		
	A1 (Cow manure 20 t ha-1)	BA = Bio-ameliorant 4 t ha-1	A = Ameliorant 4 t ha-1
CF = NPK 300 kg ha^{-1}	**8.11 a** **A**	4.42 a B	**8.33 a** **A**
DF = Nutrient solution 1600 ppm (NS)	**8.46 a** **A**	3.88 a B	3.03 b B
NDF = Oxygenated DF with 6.5 mg L^{-1} DO	**10.59 a** **A**	4.89 a B	2.13 b B

Note: numbers followed by the same letter are not significantly different according to the Duncan-DMRT follow-up test at a 5% significance level. Lowercase letters are read vertically, comparing the two Nutritional Delivery Methods (N) within the same Soil Amendment (A). Uppercase letters are read horizontally, comparing the two Soil Amendments (A) within the same Nutritional Delivery Method (N).

but it requires careful management to avoid the risks associated with antibiotic resistance genes (ARGs) (Jauregi et al., 2021; Urra et al., 2019). Bio-ameliorants improve soil quality and microbial activity, particularly in saline soils. Other ameliorants, such as gypsum, are effective in improving soil structure and fertility, resulting in increased crop productivity.

Correlation between variables

The Pearson correlation (Figure 3) shows the correlations between observing parameters that undergo significant interactions, such as available phosphorus, exchangeable potassium, dissolved oxygen in soil (soil oxygen content), grade A, grade B, grade C, number of fruit per plant, and weight per fruit. Strong positive correlations were observed between the number of fruits per plant (NOFPP) and available phosphorus (AP) (r=0.69). A moderate positive correlation was observed between NOFPP and exchangeable potassium (EP) (r=0.45), between phosphate solubilizing bacteria (PSB) population and Available Phosphorus (AP) (r=0.42). Grade A showed a strong negative correlation with Grades B and C (r = 0.65 and r = 0.64, respectively). These results show that the higher the quality of A, the higher the quality of B and C will be curated

PCA biplot

Figure 4 presents a PCA biplot that reveals the correlations between numerous agronomic and yield-related variables of chili plants, as well as the various treatment combinations. The first two main components (PC1 and PC2) account for 68.3% of the overall variation, with PC1 (Dim1) providing 41.8% and PC2 (Dim2) accounting for 26.5%. Each arrow represents a measured variable, and its direction and length indicate the intensity of the variable and contribution to the major components. Black dots represent a combination of treatments, while the proximity of the variables shows the correlation and effect of the treatment on the measurement variables.

The analysis reveals that Grade A, dissolve oxygen soil (DOS) or known as soil oxygen content (SOC), exchangeable potassium (EP), available potassium (AP), number of fruit per plant (NOFPP), and phosphate solubilizing bacteria (PSB) population are strongly clustered in the positive direction of Dim1, indicating a strong

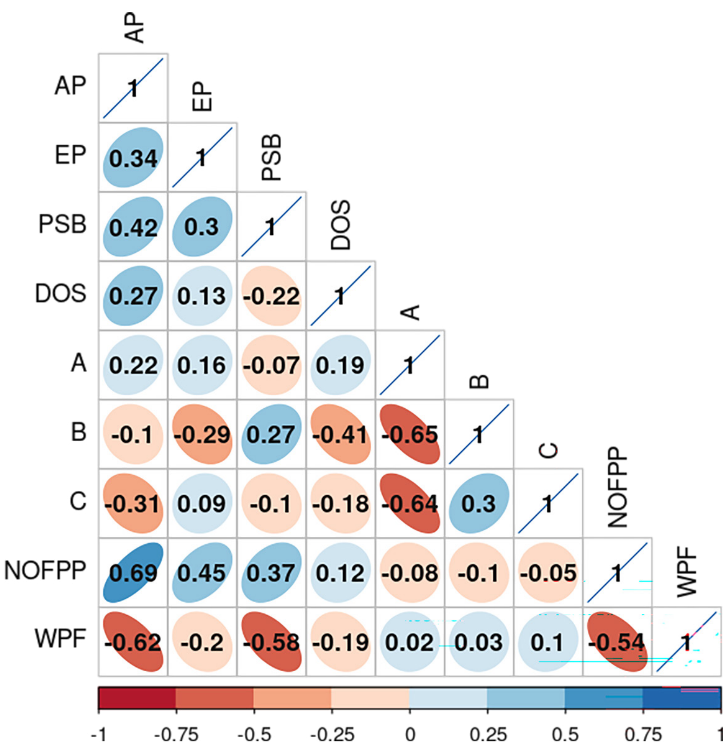

Figure 3. Correlation analysis of soil biochemical properties, plant growth, yield, and quality of the chili plant. Parameters include available phosphorus (AP), exchangeable potassium (EP), dissolved oxygen in soil (DOS), grade A (A), grade B (B), grade C (C), number of fruits per plant (NOFPP), and weight per fruit (WPF)

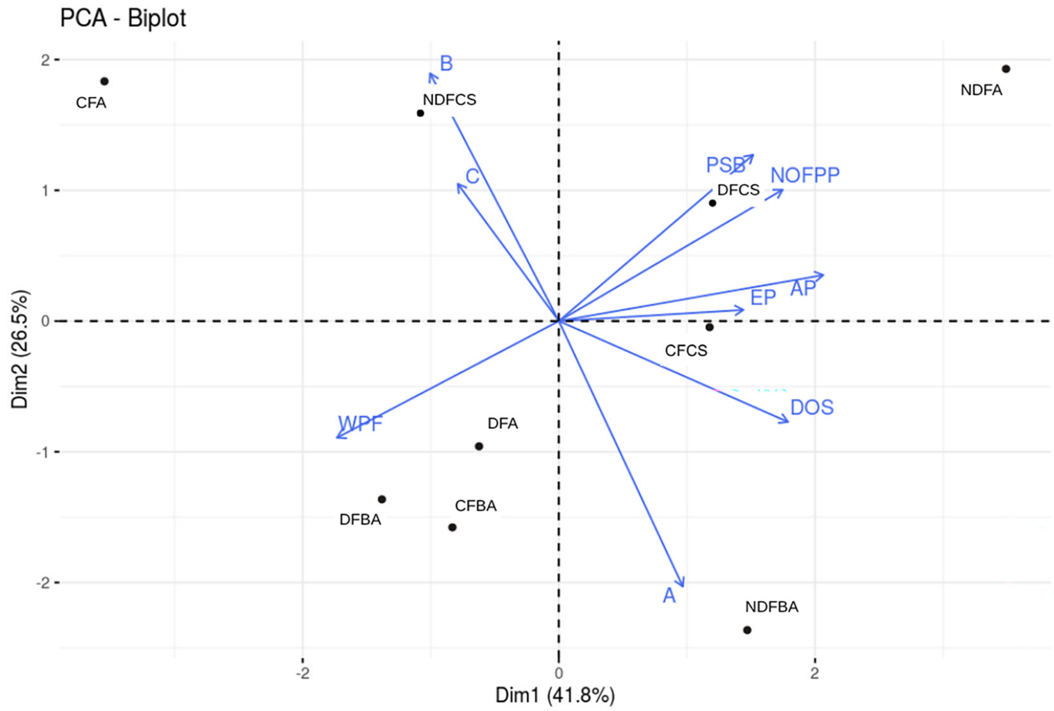

Figure 4. Principal component analysis (PCA) biplot showing the relationship between soil biochemical properties and treatments. Parameters include available phosphorus (AP), exchangeable potassium (EP), phosphate solubilizing bacteria (PSB), dissolved oxygen in soil (DOS), Grade A (A), Grade B (B), Grade C (C), number of fruits per plant (NOFPP), and weight per fruit (WPF)

correlation between these variables and quality of chili. In the quality parameters of Grade A and DOS, also known as SOC, will be greater in the NDFBA treatment (Oxygenated DF with 6.5 mg L^{-1} DO + bio-ameliorant 4 t ha^{-1}), grade B (B), grade C (C), NOFPP, and weight per fruit (WPF)

Meanwhile, other variables, such as exchangeable potassium (EP), available potassium (AP), number of fruits per plant (NOFPP), and PSB population were correlated in the treatment of CFCS (NPK 300 kg ha^{-1} + cow manure 20 t ha^{-1}) and DFCS (NS 1600 ppm + cow manure 20 t ha-1). In this cluster, the position of the NDFBA treatment is closest to the A line, indicating that the treatment has a positive impact on the quality of chili yields

Path analysis

Significantly correlated factors were then analyzed using stepwise regression to determine which had the largest influence on yield components. The stepwise regression results formed the basis for path analysis, which was used to assess the direct and indirect effects of response factors on yield variables (Figure 5). Pathway analysis was conducted to evaluate the direct and indirect effects of the variables on each other. This analysis helps distinguish between direct and indirect influences on chili crop yields. The green arrow indicates a positive effect, and the thickness of the arrow reflects the strength of the relationship.

The strongest direct effect on YWPP was contributed by NOFPP (path coefficient = 0.91), indicating that the number of fruits is a determinant of the overall yield weight of the chili plant. These results suggest that increasing the number of fruits per crop is the primary strategy for enhancing crop yields. Similar findings were reported by Subedi et al. (2023), who found that fruit number strongly influenced the total yield in chili.

The use of bio-ameliorants and nanobubbles has strong potential to enhance soil health and mitigate environmental impacts. Biochar, nanobiochar, and nanobiostimulators improve the soil microbiome and reduce N_2O, CH_4, and CO_2 emissions (Gao et al., 2022; Sultan et al., 2024). Nanobubbles enhance microbial detoxification and metabolic processes, and indirectly reduce GHG emissions by improving pollutant degradation (Zou et al., 2025). However, their long-term ecological impacts and interactions with soil components must be carefully assessed to ensure sustainable application.

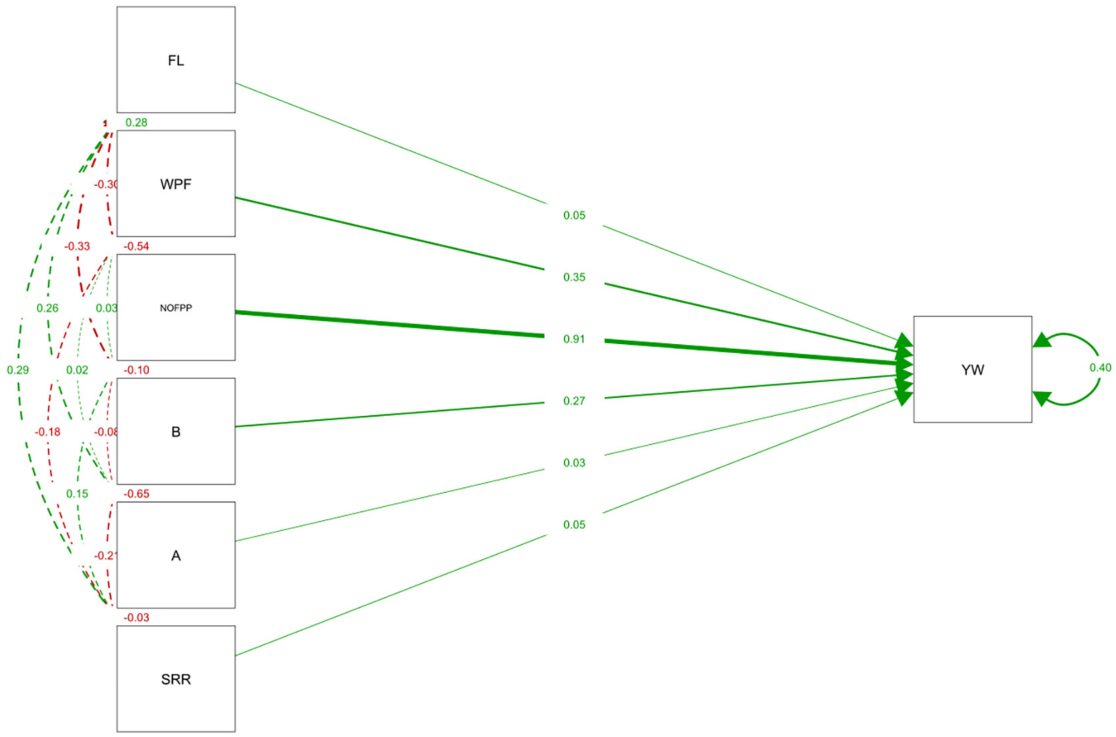

Figure 5. A model describing the relationship between attributing factors and chili yield, highlighting the direct and indirect effects of key response variables (fruit length (FL), weight per fruit (WPF), number of fruits per plant (NOFPP), grade A (A), grade B (B), soil oxygen content (SOC) on yield weight per plant (YW)

This study fills a gap in the literature by providing an in-depth analysis of the synergistic effects between nanobubble fertigation technology and soil amendments, which have not been widely researched before, especially in chili plants. By examining the correlation between parameters that influence yield quality, this study offers new insights that can help farmers understand the factors contributing to increased productivity.

The study results show that the application of this innovative technology can reduce farmers' dependence on conventional methods by offering more efficient and sustainable solutions. In addition, the prediction model developed in this study provides practical guidance for farmers to select the optimal method for improving nutrients and soil, thereby significantly enhancing the quality and yield of chili.

CONCLUSIONS

The results highlight the synergistic effects of nanobubble drip-fertigation technology and bio-ameliorant in enhancing soil biochemical properties, plant growth, yield, and chili fruit quality. The NDFBA treatment, which combined nanobubble-enriched nutrients containing 6.5 mg L^{-1} dissolved oxygen with 4 t ha^{-1} of bio-ameliorant, significantly increased soil nutrient availability and microbial activity. Furthermore, the improvement in Grade A fruit quality (79.33%) demonstrates a positive interaction between nanobubble fertigation and bio-ameliorant applications in enhancing chili productivity and quality. This research contributes to sustainable agriculture by offering practical, low-cost solutions for smallholder farmers to improve both yield and product quality. Theoretically, it advances understanding of the interactions between fertigation technology and soil conditioners in chili cultivation. At the same time, practically, it provides a foundation for developing more efficient and environmentally friendly production systems. This study was conducted at a single site and focused on one crop species, which may limit the generalizability of the findings. Moreover, the dissolved oxygen concentration reached only 6.5 mg L^{-1}, indicating the need for further optimization of oxygen enrichment. Future research should aim to enhance oxygen levels (≥9 mg L^{-1}) and comprehensively evaluate the scalability, cost-effectiveness, and long-term sustainability of the nanobubble drip fertigation

+ bio-ameliorant system. Validation across multiple planting seasons, soil types, and open-field conditions is also recommended to capture temporal and spatial variability and to assess the system's adaptability and agronomic performance under diverse agroecological contexts.

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