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Deep insights into drip-based nanobubble fertigation technology for enhancing nutrient availability and boosting cash crop vegetable productivity and quality

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ABSTRACT

Drip-based nanobubble fertigation technology (DNFT) represents a promising advancement in sustainable horticulture, particularly in the cultivation of high-value cash-crop vegetables such as chili, tomato, onion, and paprika, aiming to enhance nutrient availability, water use efficiency, and crop productivity. This research aims to comprehensively explore and assess the potential of DNFT in enhancing the sustainability of horticultural crop production. A systematic literature review and bibliometric analysis, conducted following the PRISMA framework and using Scopus and ScienceDirect search engines, resulted in 303 articles, of which 20 were deemed eligible for further review. The analysis results revealed a significant increase in DNFT-related publications over the past ten years. DNFT improves nutrient availability, microbial activity, and soil biochemical processes, boosting cash crop vegetable productivity (119%) and quality. These findings conclude that DNFT provides significant economic benefits, including water and fertilizer savings. However, challenges remain, such as the lack of comprehensive economic analysis covering costs and long-term viability across diverse farming systems. Future advancements may revolutionize vegetable production systems by enhancing yields while conserving vital resources such as water and fertilizers.

Keywords: nanobubble technology, DNFT, horticulture, soil media, drip irrigation, cash-crops.

INTRODUCTION

A cash crop vegetable is a horticultural plant, such as tomatoes, peppers, lettuce, cucumbers, and chilli, grown primarily for commercial sale rather than for personal consumption or local use. These crops are cultivated with the primary objective of generating income for farmers, who often target both domestic and international markets. Cash crops play a vital role in commercial agriculture due to their consistently strong market demand and high profitability. Cash crops play a crucial role in poverty alleviation by directly increasing farmers' income, strengthening food security, and enhancing resilience to economic shocks, while also indirectly fostering rural economic stability through employment opportunities and sustained income generation (Singh et al., 2024). Cultivating cash crops also helps rural development by improving infrastructure, stimulating local economies, and providing opportunities for smallholder farmers. Additionally, cash crops are increasingly valued for their ability to diversify farming practices, reduce dependency on a single crop, and promote economic resilience in agricultural systems (Sasikala, 2022).

The production of cash crops faces several agronomic and environmental challenges, including inefficient water and fertilizer use, declining soil fertility, erosion, excessive herbicide application, and low resource-use efficiency (Rajametov et al., 2021; Rajeswari et al., 2024). In addition, given the pressing issues of water scarcity and climate change, conserving water in agriculture is becoming increasingly essential (Ardiansyah et al., 2024). These issues, exacerbated by a reliance on external inputs, threaten the long-term sustainability of crop production, particularly in terms of yield stability, resource efficiency, and environmental impact (Lairez et al., 2023; Liao et al., 2021; Zhang et al., 2023). To address these challenges, there is a critical need for improved agronomic practices that promote sustainable farming. By optimizing resource use and minimizing environmental harm, such practices can ensure the continued productivity and resilience of cash crop farming in the face of these growing concerns.

Addressing these challenges requires the integration of advanced technological innovations, with drip fertigation recognized as one of the most effective solutions. Drip fertigation systems deliver water and nutrients directly to the plant root zone, minimizing waste and improving plant health (Cui et al., 2022; Rane et al., 2024). In this context, drip-based nanobubble fertigation technology (DNFT) has emerged as a promising hybrid solution. DNFT combines the precision of conventional drip fertigation systems with the advantages of nanobubble technology—ultra-fine gas bubbles with high stability that enhance oxygen delivery to the root zone (DeBoer et al, 2024; Zhang et al., 2024). This combination improves nutrient uptake and creates a healthier rhizosphere by stimulating beneficial microbial activity.

Furthermore, precision agriculture technologies such as DNFT play a crucial role in supporting the achievement of the sustainable development goals (SDGs), particularly SDG 1 (No Poverty) and SDG 2 (Zero Hunger), by increasing agricultural productivity and resource use efficiency. Additionally, this approach contributes to environmental sustainability and strengthens climate change mitigation efforts (Fauziah et al., 2024). As a result, DNFT holds significant potential to improve crop management, increase yield productivity, and promote environmentally friendly and sustainable agricultural practices (Baram et al., 2022). Nanobubbles enhance soil structure by improving its porosity and permeability and facilitating better water and nutrient absorption by plant roots (Chen et al., 2023). Furthermore, nanobubbles increase oxygen solubility in irrigation solutions, optimizing nutrient efficiency and promoting the growth of beneficial microbes in the rhizosphere (Jannesari et al., 2024; Chen et al 2023). This synergistic effect of improved oxygen delivery and microbial activity is believed to enhance crop quality and productivity while fostering healthier soil ecosystems (Tan et al., 2024; Lei et al, 2023). Additionally, by increasing resource-use efficiency, DNFT offers a sustainable solution to the challenges faced by conventional agricultural systems. As a result, DNFT holds significant potential in supporting long-term agricultural sustainability.

This study aims to provide a comprehensive and structured synthesis of the existing research on DNFT through a Systematic Literature Review (SLR) and bibliometric analysis following the PRISMA framework. Specifically, the review seeks to (1) evaluate the impact of DNFT on rhizosphere microbial activity and soil biochemical properties, with a particular focus on nutrient cycling and plant-microbe interactions, (2) assess how DNFT contributes to the long-term sustainability of horticultural production, including crop yield stability and resource-use efficiency, while also evaluating its economic benefits, such as water and fertilizer savings, yield improvements, and return on investment, (3) identify current limitations and challenges related to the implementation of DNFT in horticultural systems, and (4) explore the prospects for scaling DNFT as a climate-resilient and sustainable innovation in modern agriculture. The study provides a holistic understanding of DNFT's potential to transform agricultural practices by addressing these objectives.

MATERIALS AND METHODS

Search analysis in Scopus and ScienceDirect

A bibliometric analysis and systematic literature review were carried out by searching conducted across Scopus, and ScienceDirect databases for studies published between 2015 and 2025. the results were gathered using a set of keywords that included "nanobubble", "vegetable", "chili", "onion", "tomato", "bell pepper", "drip", "irrigation", "fertigation", "water", "efficiency", "nutrient", "rhizosphere", "microbe", "productivity", and "yield". The comprehensive search strategy is presented in Table 1. The information on the number of articles published in different categories, such as journals, years, and countries was exported and analysed.

Data retrieval for bibliometric analysis

Data for this bibliometric analysis were collected from the Scopus and ScienceDirect databases. The search terms and their combinations used several keywords. The search was limited to research articles with date of publication 2015–2025. The language of publication was limited to English. The bibliographic data gathered from the search results was exported in RIS format and then analysed using VOSviewer version 1.6.19

Systematic literature review using PRISMA

Relevant articles were sourced and retrieved from the database in RIS format for subsequent analysis. The exclusion and inclusion criteria are presented in Table 2. Data retrieved from Scopus and Science Direct were then assessed using systematic literature review (Figure 1). Duplications were eliminated using Mendeley Reference Manager 2.107.0. Eligibility of the documents included was based on the abstract related to the topic of the article; documents not related to the topic were categorized as ineligible and thus not included for further content analysis.

RESULTS AND DISCUSSION

Bibliometric analysis result

Figure 2 presents a co-occurrence network visualization of author keywords related to DNFT, generated using VOSviewer with the full counting method. This bibliometric analysis was conducted on research articles published over the past ten years to uncover emerging themes, research trends, and the interconnectedness of key concepts in the field. A minimum occurrence threshold was applied to identify the most frequently used author keywords. From a refined set of 68 frequently occurring keywords, *plant* stands out as the most central and interconnected term, acting as a bridge between all thematic clusters. Its central location and strong co-occurrence with keywords across clusters – such as nutrient, field experiment, nitrogen, and agriculture – indicate

Table 1. Approach used to gather applicable research articles

Search strategy	Scopus	Science direct
"nanobubble" AND ("vegetable" OR "chili" OR "tomato" OR "onion" OR "bell pepper") AND "drip" AND "irrigation"	1	5
"fertigation" AND "water" AND "efficiency" AND "nutrient" AND ("vegetable" OR "chili" OR "tomato" OR "onion" OR "bell pepper")	29	181
"rhizosphere" AND "drip" AND "irrigation" AND "microbe"	12	61
"drip" AND ("irrigation" OR "nanobubble") AND "productivity" AND vegetable OR chili OR tomato OR onion OR bell pepper("vegetable" OR "chili" OR "tomato" OR "onion" OR "bell pepper")	81	2
("nanobubble" or "drip") AND "irrigation" and "fertigation" AND "yield" AND ("vegetable" OR "chili" OR "tomato" OR "onion" OR "bell pepper")	33	1

Table 2. Criteria for inclusion and exclusion applied in this study

Criteria	Inclusion	Exclusion
Relevance topics	Article related to DNFT for enhancing nutrient availability and boosting cash-crop vegetable productivity and quality	Journal unrelated to DNFT for enhancing nutrient availability and boosting cash-crop vegetable productivity and quality
Date of publication	2015–2025	Years before 2015
Type of publication	Research article	Books chapter, Encyclopedia, News, Conference abstracts
Language of publication	English	All other language
Access	Open access	No open access
Databases	Scopus and Science Direct	Article that are not indexed by Scopus or Science Direct

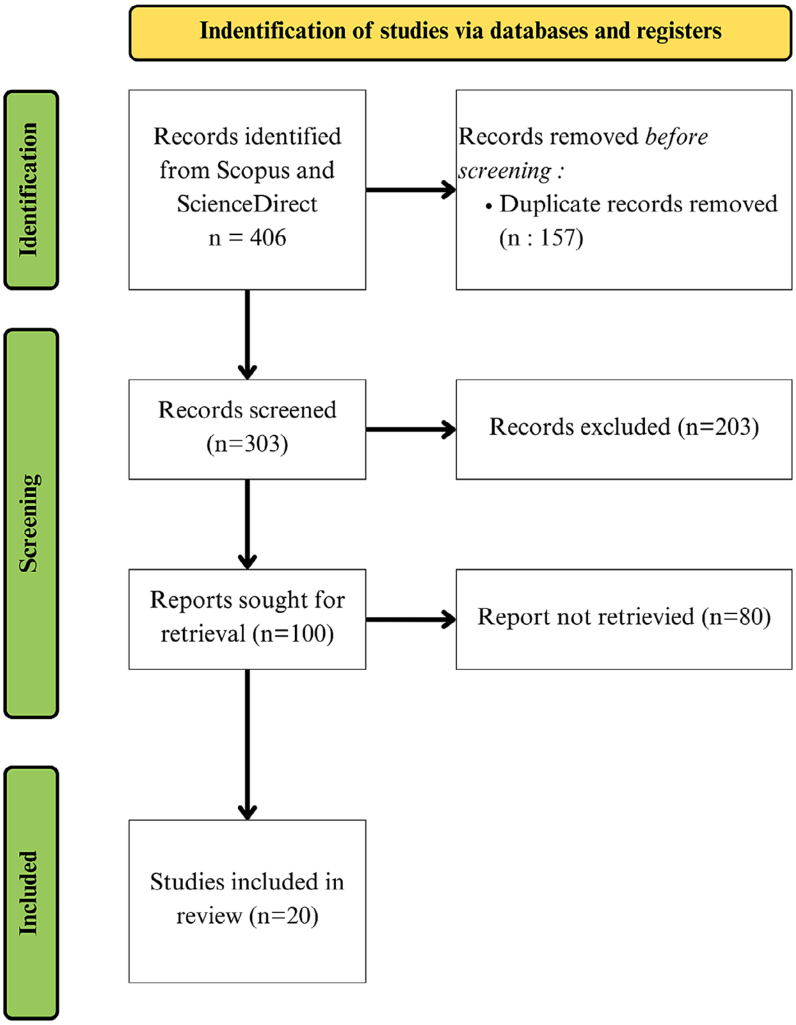

Figure 1. PRISMA flowchart illustrating the process of selecting articles for the systematic literature review

its foundational role in research exploring plant response to innovations like nanobubble fertigation. Overall, the keyword co-occurrence mapping in Figure 2 provides a comprehensive overview of the evolving landscape of studies aimed at exploring the impact of nanobubble fertigation on plant growth, yield, and nutrient uptake – core outcomes in this area.

Based on the results of the bibliometric analysis, research on DNFT for enhancing nutrient availability and boosting cash-crop vegetable productivity and quality is categorised into three clusters (Table 3). All clusters are interconnected, with no significant differences among the keywords. The first cluster (Red) encompasses broader systemic and environmental aspects of agriculture, particularly concerning irrigation management and sustainability. Terms such as adoption, agriculture, climate change, water scarcity, and sustainability highlight the global pressures facing modern farming. These include diminishing water availability and the urgent need to transition toward more efficient irrigation systems like drip irrigation. The cluster also contains terms like drip irrigation system, irrigation scheduling, soil moisture, and water use, which collectively reflect the ongoing shift in irrigation practices aimed at maximizing water productivity and crop output in a resource-constrained environment. Importantly, the presence of words like farmer, field, and technology underscores the role of technology adoption and its practical implementation in the field. This aligns with the central focus of the article, which proposes nanobubble-enriched fertigation systems as a sustainable solution to overcome climate-induced agricultural constraints, especially in vegetable production systems.

Cluster 2 (Green) represents the agronomic and experimental dimensions of drip fertigation, especially focused on tomato cultivation. This

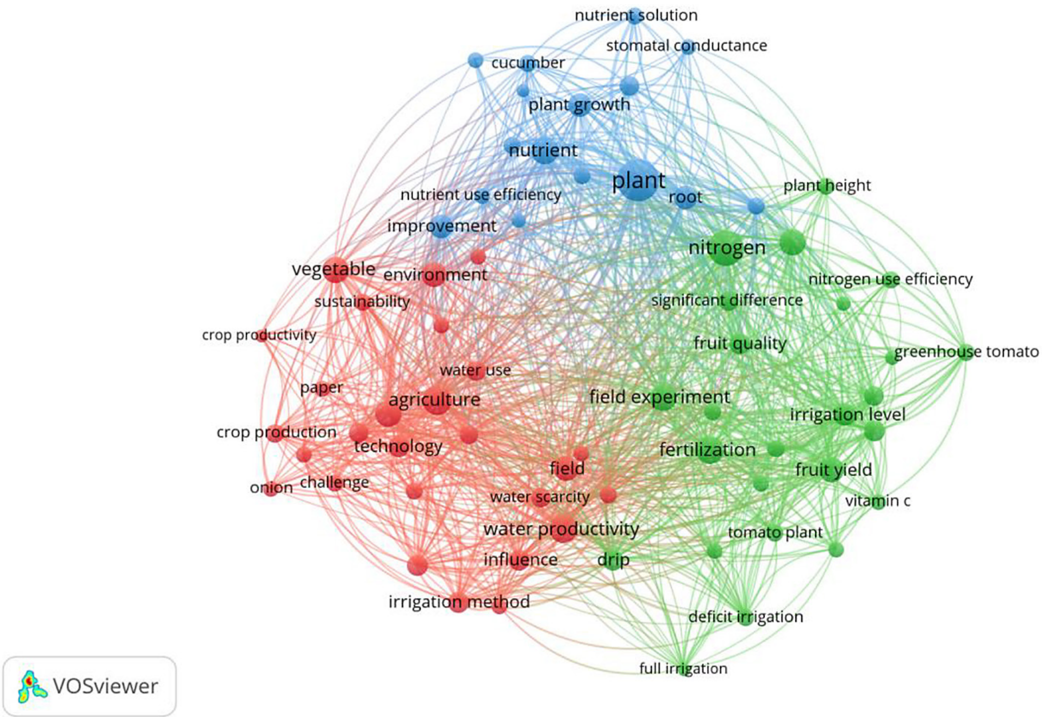

Figure 2. A network visualisation of the co-occurrence mapping of pertinent keywords related

Table 3. A selection of terms organised into clusters according to the analysis of textual data

Cluster 1	Cluster 2	Cluster 3
Adoption, agriculture, challenge, climate change, crop production, crop productivity, drip irrigation system, environment, evaluation, farmer, field, influence, irrigation method, irrigation scheduling, irrigation system, onion, paper, soil moisture, soil water content, surface, sustainability, technology, vegetable, vegetable production, water productivity, water scarcity, water use	Combination, crop evapotranspiration, crop growth, deficit irrigation, drip, drip fertigation, fertilization, field experiment, fruit quality, fruit yield, full irrigation, greenhouse tomato, growth stage, irrigation level, nitrogen, nitrogen application, nitrogen use efficiency, plant height, significant effect, soil water, solanum lycopersicum l, tomato plant, tomato yield, vitamin c	Cucumber, dry matter, improvement, irrigation water productivity, leafe, lettuce, nutrient, nutrient solution, nutrient use efficiency, phosphorus, plant, plant growth, potassium, present study, root, stomatal conductance

cluster contains terms such as crop evapotranspiration, deficit irrigation, field experiment, fruit yield, nitrogen use efficiency, and vitamin C, which point to the measurement of both growth and quality outcomes under different irrigation regimes. The emphasis on drip fertigation, nitrogen application, and greenhouse tomato directly connects with the article's exploration of nanobubble technology as a method to improve nutrient delivery through irrigation systems. By enhancing water and nitrogen use efficiency, the technology contributes to improved yield, quality, and reduced environmental impact. Terms like significant effect, growth stage, and plant height also suggest a focus on the experimental validation of fertigation methods, which supports the article's evidence-based approach. This cluster shows how innovations are not only tested under controlled conditions but also evaluated based on measurable physiological and biochemical indicators.

Cluster 3 (Blue) focuses on the physiological and biochemical responses of plants to irrigation and nutrient strategies, with an emphasis on crops like cucumber and lettuce. It includes terms such as nutrient use efficiency, phosphorus, potassium, stomatal conductance, root, and plant growth, which suggest a microscopic exploration of how enhanced irrigation (especially with nutrient-rich solutions) affects nutrient uptake, internal plant functions, and biomass accumulation. The cluster supports the article's hypothesis that nanobubbles can improve nutrient solubility and root zone aeration, thereby enhancing nutrient absorption, water uptake, and physiological health of plants.

These mechanisms are essential for understanding how nanobubble fertigation boosts productivity and fruit quality in vegetable crops, aligning with the article's goal to improve overall crop value and resource efficiency.

Together, these three clusters form a cohesive research landscape that supports the article's Together, these clusters reflect a cohesive and multidimensional research landscape that addresses environmental sustainability, practical field experimentation, and plant-level physiological mechanisms. As shown in Figure 3, recent trends indicate a growing focus on sustainability and plant-environment interactions. Keywords such as sustainability, vegetable, cucumber, nutrient use efficiency, and plant growth, highlighted in yellow, have gained prominence in 2022 and 2023. Although some recent publications are not yet fully indexed, the network suggests an ongoing shift toward sustainable, high-efficiency fertigation systems aligned with the goals of precision agriculture and climate-resilient farming.

Recent advancements in agricultural research highlight a growing interest in the integration of innovative irrigation technologies, particularly DNFT, for improving crop productivity and sustainability. An overlay visualization map generated through VOSviewer reveals current and emerging research trends related to this topic, drawing insights from keyword co-occurrence across scientific publications. Core terms such as plant, nitrogen, field, fertilization, agriculture, and water productivity appear prominently at the center of the network, indicating their foundational role in the broader discourse on nutrient management and crop performance. These keywords are generally colored in shades of green and blue, suggesting consistent attention between 2021 and 2022.

Notably, the map also highlights a shift in focus through the emergence of yellow-toned keywords such as greenhouse tomato, cucumber, sustainability, environment, nutrient use efficiency, water scarcity, and vitamin C. These terms, gaining prominence in late 2022 and throughout 2023, suggest a growing concern with sustainable intensification – aiming to optimize water and nutrient use while enhancing the quality of horticultural produce. The inclusion of crop-specific terms like greenhouse tomato and cucumber indicates a more targeted approach in recent research, focusing on high-value vegetable crops and their physiological and nutritional responses to nanobubble-enriched fertigation. Peripheral keywords such as deficit irrigation, drip, technology, and challenge highlight the ongoing efforts to refine irrigation strategies in response to limited water availability and environmental constraints. These terms point to the practical applications of DNFT in addressing critical issues like water efficiency and nutrient delivery in agriculture. The inclusion of vitamin C reflects a broader interest in crop quality, indicating that research is not only focused on yield improvement but also on

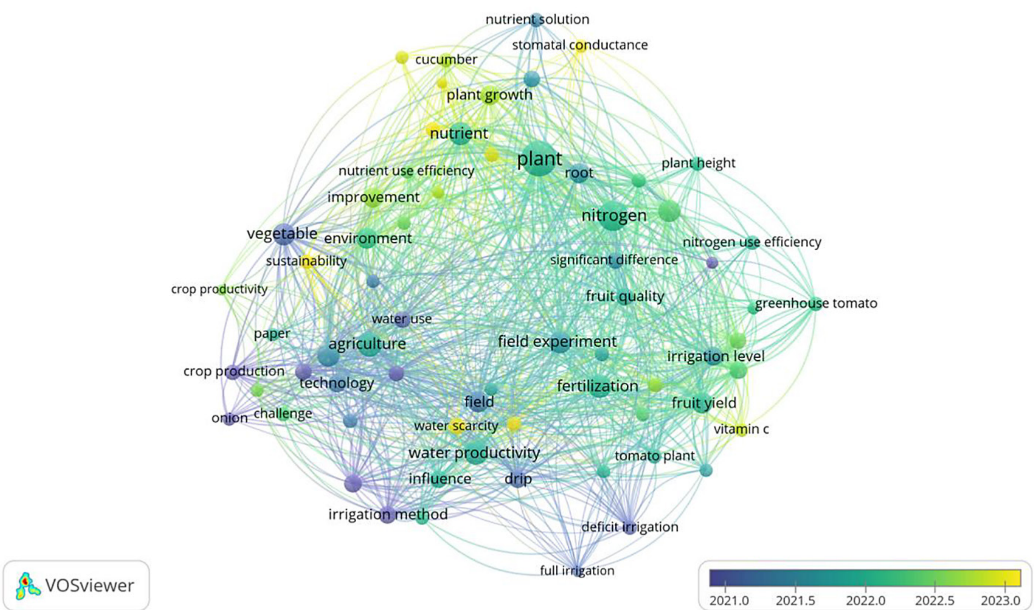

Figure 3. An overlay visualisation of the publication year mapping related

enhancing the nutritional value and marketability of produce. This shift suggests a more holistic approach, where both productivity and crop quality are integral to sustainable farming outcomes.

Collectively, this bibliometric trend analysis demonstrates that research surrounding DNFT is evolving toward holistic, resource-efficient, and quality-focused agricultural practices. It affirms the relevance of exploring this technology as a forward-looking strategy for enhancing nutrient availability, improving water use, and boosting both the productivity and quality of cash crop vegetables. These insights provide a strong foundation for further research and practical applications in sustainable agriculture.

Definition and concept of nanobubble fertigation technology

Drip irrigation is a precision farming technique that determines the specific water and fertilizer needs of crops at different growth stages by applying the principle of soil nutrient and water balance. It then delivers these inputs directly and gradually to the root zone through a controlled drip system, thereby enhancing fertilizer efficiency and minimizing water usage (Yang et al. 2023). In the context of protected agriculture, efficient management of water and nutrients is crucial, as it directly influences both economic outcomes and environmental sustainability. Fertigation, the integration of fertilization and irrigation, is commonly utilized in such systems to maximize resource use efficiency (Lin et al. 2020). Additionally, managing irrigation and fertigation independently allows for more accurate adjustments in water and nutrient delivery based on the specific needs of the plants, fostering healthier and more consistent growth (Adamo et al. 2025). The integration of nanobubble technology into fertigation systems further enhances this precision. Research has shown that using nanobubble irrigation can provide various benefits to plants. By improving root growth and vitality, increasing crop yields, water use efficiency, and fruit quality (Liu et al. 2019). The positive responses generated by nanobubbles are likely related to improved soil nutrient availability (HU et al. 2020). The presence of NBs can enhance nutrient availability and absorption by plants, helping to transport nutrients from the soil to the plant root zone (Xue et al., 2023). Nanobubbles (NBs) are ultra-fine gas-filled bubbles with diameters less than 1 μm, capable of carrying various gases such as oxygen, nitrogen, and hydrogen (Zhao et al., 2023). Due to their extremely small size and large surface area, NBs interact effectively with surrounding environments such as soil and water, making them highly valuable for applications in agriculture, water treatment, and environmental remediation. There are numerous applications in various fields as medicine, biology, chemistry, agriculture, decontamination, materials science, food technology, etc (Foudas et al., 2023). NBs have gained increasing attention in the agricultural sector for their ability to enhance plant growth, reduce reliance on chemical fertilizers, mitigate nutrient losses, and minimize environmental pollution by increasing nutrient solution oxygen dissolution and promoting plant development (Zhou et al., 2022; Gobai et al., 2025; Hasta et al., 2021). These advantages contribute to global sustainable development goals, particularly those addressing climate action and responsible resource management.

A significant innovation in this domain is nanobubble fertigation technology (NFT), which integrates nanobubbles into irrigation systems to improve plant growth, nutrient uptake, and soil health. The beneficial effects of NFT are largely attributed to improved nutrient bioavailability in the rhizosphere (Hu et al., 2020). Drip fertigation can provide water and fertilizer directly to the crop root zone conveniently and efficiently and reduce irrigation and fertilizer input (Feng et al., 2023). NBs facilitate nutrient transport from the soil to plant roots, enhancing nutrient uptake efficiency (Xue et al., 2023). Typically, NFT involves combining nanobubble-enriched irrigation water with dissolved fertilizers delivered through systems such as drip irrigation, enabling the direct and efficient delivery of gases and nutrients to the root zone.

For example, Wang et al. (2021) demonstrated that applying nanobubbles to rice seedlings significantly increased plant height and root length, while also promoting gibberellin production—a key hormone regulating plant growth. Moreover, the expression of genes associated with nutrient uptake was upregulated, contributing to improved nutrient absorption and utilization. Similarly, He et al. (2022) reported that nanobubble application in watermelon and melon cultivation reduced irrigation and fertilizer requirements by up to 20% without compromising plant development or fruit quality. Nanobubble fertigation is particularly effective in high-value horticultural crops such as tomatoes, chilies, onions, and bell peppers. These crops benefit from enhanced water-use efficiency, stimulated microbial activity in the rhizosphere, improved nutrient availability, and increased crop yield and quality. Consequently, NFT offers a sustainable, resource-efficient solution for intensive horticultural systems. This study aims to explore and evaluate the current advancements and future potential of nanobubble fertigation technology as an innovative approach to enhancing nutrient bioavailability, promoting rhizosphere biological activity, and supporting the overall growth and productivity of agricultural crops

Microbial activity and rhizosphere quality

The rhizosphere, the microbiological zone surrounding plant roots, plays a crucial role in plant growth and development. This zone facilitates the interaction between plant roots and soil microorganisms, such as bacteria, fungi, and other microbes, which influence nutrient cycling, soil health, and plant performance. Microbial activity in the rhizosphere is fundamental to several key processes, including nitrogen fixation, organic matter decomposition, and the regulation of soil pH. These activities enhance nutrient availability to plants, contributing to overall soil fertility. Consequently, the quality of the rhizosphere significantly affects plant health and agricultural productivity. In recent years, the advent of nanobubble fertigation technology has provided new opportunities for modulating the rhizosphere environment, potentially improving microbial activity and soil quality. Nanobubbles, which are extremely small gas bubbles that enhance oxygen dissolution in irrigation water, have the potential to alter microbial dynamics and improve soil conditions, offering a promising approach to sustainable agricultural practices (Zhou et al., 2021; Wang et al., 2024)

Nanobubble fertigation technology significantly enhances microbial activity and improves rhizosphere quality by increasing the availability of dissolved oxygen and optimizing the soil-root microenvironment. transfer efficiency, and the ability to penetrate soil pores and biofilms, thereby promoting aerobic microbial processes (Chen et al., 2023; Zhou et al., 2021). Increased oxygen levels in the root zone foster the proliferation of beneficial aerobic microorganisms, such as nitrifying bacteria and phosphate-solubilizing microbes, which enhance nutrient cycling and uptake (Wang et al., 2023). The enriched oxygen environment created by nanobubble irrigation supports root respiration and promotes the development of fine root structures, further enhancing microbial colonization. Additionally, nanobubbles have been shown to reduce the prevalence of pathogenic anaerobic bacteria, contributing to a healthier rhizosphere ecosystem (Wang et al., 2024). These improvements in microbial dynamics and soil biological activity contribute to better plant growth, nutrient use efficiency, and long-term soil fertility.

Table 4. Impact of drip fertigation on microbial activity and rhizosphere quality in cash crops

Cash crop	Technologies used	Impact on microbial activity	Impact on rhizosphere quality	References
Tomato	Drip Irrigation Aerated with Micro/Nanobubbles at Different Dissolved Oxygen Levels	Significantly enhances the metabolic diversity of bacterial communities in the root–soil continuum, particularly promoting *Paenibacillus* spp.	Increased soil nitrogen and phosphorus availability	Wang et al., 2023
Strawberry	Drip irrigation using micro–nanobubble water (MNBW) enriched with potassium sulfate (K_2SO_4)	Increased abundance of beneficial microbes: *Bacillus*, *Steroidobacter*, *Streptomyces*, *Thermopolyspora*, *Microbispora*.	Increased soil temperature and organic matter decomposition; improved soil fertility via elevated oxygen levels	Wang et al., 2023
Chili	Drip irrigation supplemented with hydrogen peroxide (H_2O_2)	Enhanced microbial carbon, respiration, and enzymatic activity	Increased soil C, N, and pH levels	Thomaset al., 2025
Cucumber	Drip irrigation with low mineralization degree of irrigation water	Increased abundance of soil bacteria and fungi	Significantly increased soil respiration and enzyme activity	Ouyang et al., 2024
Onion	Drip Irrigation	Higher fungal and actinobacterial abundance than in sprinkle and furrow irrigation	Reduced soil EC and Exchangeable Sodium Percentage	Selvamurugan et al., 2024

The application of various fertigation technologies has significantly improved microbial activity and rhizosphere quality in a range of cash crops, as presented in Table 4. For tomatoes, the use of micro/nanobubble aerated drip irrigation increased the metabolic diversity of bacterial communities and improved nutrient availability, especially nitrogen and phosphorus (Wang et al., 2024). In strawberries, micro/nanobubble water enriched with potassium sulfate promoted beneficial microbes, increased soil temperature, and improved organic matter decomposition (Wang et al., 2024). For chili, hydrogen peroxide supplementation enhanced microbial activity, boosting soil carbon, nitrogen, and pH levels (Thomas et al., 2025). Similarly, cucumber irrigation with low mineralization water increased microbial abundance, respiration, and enzyme activity (Ouyang et al., 2024). Finally, onion crops showed better microbial diversity and improved soil health with drip irrigation compared to other methods (Selvamurugan et al., 2024). Overall, these technologies optimize microbial dynamics, improve soil fertility, and promote better plant growth, supporting sustainable agricultural practices.

Nutrient availability and sustainability of crop productivity

Nanobubble fertigation technology (NBFT) is emerging as a cutting-edge innovation in sustainable agriculture, particularly beneficial for high-value vegetable crops such as tomato, chili, and onion. One of the notable advantages of NBFT is its ability to enhance soil carbon content and nutrient availability—key indicators of soil fertility and productivity. These improvements can be effectively achieved through nanobubble generation (NBG) systems. Nanobubbles (NBs) possess distinct physicochemical properties, including prolonged stability, high gas solubility, strong adsorption potential, a large specific surface area, and high internal pressure, all of which contribute to their efficacy in enhancing nutrient dynamics within the soil-plant system (Pal and Anantharaman, 2022).

Numerous studies have confirmed that nanobubbles significantly improve nutrient uptake by both soil and plants, thereby promoting better plant growth and physiological development. According to Chen et al. (2023), nanobubble application improves soil structure by increasing total porosity and pore connectivity, facilitating enhanced water and nutrient transport to plant roots. In addition, oxygen nanobubbles (ONBs) have been shown to accelerate seed germination and early vegetative growth, which can lead to higher crop yields (Xue et al., 2023). Beyond improving soil properties and nutrient transport, nanobubbles support the development of healthier and more extensive root systems, allowing plants to absorb nutrients more efficiently. This is especially advantageous in organic farming, where external nutrient inputs are limited. Evidence also suggests that the application of nanobubble-enriched irrigation water can lead to significant yield improvements in organic tomato production. Furthermore, nanobubble gas dissolution (GDS) or NBG systems have the potential to mitigate CO_2 emissions by redirecting atmospheric carbon for beneficial use in plant growth (Pal and Anantharaman, 2022).

Taken together, these findings underscore the considerable potential of nanobubble technology in promoting sustainable and resilient agricultural practices. By enhancing soil nutrient availability, improving nutrient use efficiency, and supporting robust plant growth, NBFT represents a promising strategy for increasing crop productivity while maintaining long-term soil health.

The application of advanced fertigation technologies, such as drip-based systems combined with nanobubble treatments, has led to significant improvements in the productivity and quality of various vegetable crops. As outlined in Table 5, research has shown that these technologies can increase vegetable yields by up to 119%. For example, tomato yields have increased by 23.3% using alternate partial root-zone drip fertigation, while onion yields have nearly doubled with subsurface drip irrigation systems. The use of nanobubble oxygenated water in tomato irrigation has resulted in a 19.66% increase in yield, alongside improved fruit quality, with 26.5% more vitamin C and 20.7% more soluble sugars. Additionally, using organomineral fertilizers in combination with drip fertigation has shown to increase chili yields by up to 145 fruits per plant, while reducing chemical fertilizer use by 50%. These technologies also enhance nutrient uptake efficiency. For instance, nitrogen uptake in crops like red cabbage was increased by 14 kg N/ha compared to traditional methods. Furthermore, nanobubble irrigation has been shown to improve seed germination, stem growth, and nitrogen use efficiency, boosting plant height

Table 5. Impact of drip-based fertigation on nutrient availability and sustainability of cash crops productivity

Cash-crop	Technologies used	Impact on Yield Increased, and economic or quality increased	reference
Tomato	Alternate partial root-zone drip fertigation (ADF) at different frequencies	Improved the tomato yield by significantly increasing tomato yield 23.3% higher in the intervals of 3 days treatment, Water content increased by 7.5–15.9% in the 0–20 cm layer and 3.5–7.6% in the 20–40 cm layer, while mineral nitrogen content rose by 10.5–21.3% and 37.1–57.7% in the respective layers, enhancing nitrogen uptake by crops	Feng et al., 2023
Onion	Subsurface drip irrigation system (SDI) with NPK fertilizer at different ratios	The onion yields were approximately 119% and 95% higher for the SDI system at different yield site. The SDI system achieved high irrigation efficiency (88.5%) and irrigation use efficiency of 25.2 kg/m³ and 17.5 kg/m³ across different yield sites	Enciso et al., 2015
Tomato	Nanobubble oxygenated (NBO_2) by drip irrigation	The average tomato yield in the NBO_2 treatment was 58.51 t/hm^2 , which was 19.66% higher than that in the control treatment. NBO_2 treatment increasing vitamin C and soluble sugar contents by 26.5% and 20.7%, respectively. It also enhanced soil permeability and pore volume by 355.1% and 43.1%, while reducing aggregate size by 15.5% and soil organic carbon by 17.2%	Chen et al., 2023
Chili	fertigation with drip system using organomineral fertilizer (OMF) applied with chemical fertilizer (CF) in different ratios	improved the mean crop yields of (145 fruits/ plant) and significantly minimize chemical fertilizer by using 50% of CF and 50% of OMF in the fertigation system	Tan et al., 2023
Red Cabbage	Subsurface drip fertigation with nitrogen fertilizer	Plants in SDF plots absorbed about 14 kg N/ha more than control, showing better nitrogen use efficiency. At mid and late growth stages, N uptake was 116 and 164 kg N ha^{-1} for SDF, mostly through active nutrient uptake (92%). By the end of the season, 31.8 kg N/ha was still available in the root zone for SDF. SDF showed 84.7 kg N/ha of nitrate leaching	Callau-Beyer et al., 2024
Tomato	Irrigation aerated with oxygen nanobubble (ONBs) and Nitrogen Nanobubble (NNBs)	Increased seed germination by 10% and plant growth by 30–50% in stem height and diameter by ONBs. Promotion (7% – 34%) on plant height by NNBs	Xue et al., 2023

and diameter by 30–50%. Overall, these findings highlight the substantial potential of DNFT systems to increase productivity by up to 119%, enhance crop quality, and improve resource efficiency, making them a highly promising approach for sustainable vegetable farming.

Challenge and future prospect

DNFT is an innovative approach designed to improve nutrient availability, plant productivity, and the overall quality of vegetable crops. Nanobubble technology is increasingly recognized in the agricultural sector for its potential to enhance nutrient uptake efficiency and stimulate plant growth. Nanobubbles, which are gas-filled cavities less than 200 nm in diameter, have unique physicochemical properties that allow them to attach to nutrients and facilitate their transport directly to the rhizosphere, thereby improving bioavailability and uptake efficiency compared to conventional irrigation techniques (Liu et al., 2019). When integrated into drip irrigation systems, nanobubbles significantly increase the concentration of dissolved oxygen in irrigation water, which enhances aerobic microbial activity, root respiration, and overall nutrient absorption by plants (Marcelino et al., 2022).

However, the adoption of nanobubble technology in agriculture is not without challenges. One of the major limitations is the lack of comprehensive cost-benefit analyses that encompass not only energy consumption but also the capital investment, operational expenses, and maintenance associated with micro-nano bubble generators. Current studies primarily focus on energy efficiency post-implementation, overlooking the long-term economic implications and scalability of the technology. Thus, a key research challenge moving forward is to perform holistic evaluations of economic viability and return on investment in diverse agricultural settings. Despite these hurdles, the future outlook for nanobubble fertigation technology remains promising, particularly due to its compatibility with the objectives of sustainable and precision agriculture. Integrating technologies with farming practices allows for more efficient resource use, improved yield stability, and reduction in environmental footprints (Choudhary et al., 2025). Such technological convergence aligns with the goals of modern agriculture by enhancing both the intrinsic and extrinsic quality of produce, improving farm profitability, and reducing dependence on excessive agrochemical inputs (Sharma and Shivandu, 2024). Additionally, precision agriculture tools can provide real-time data to optimize irrigation scheduling and nutrient delivery, further amplifying the benefits of nanobubble systems.

Looking ahead, continued interdisciplinary research, strong governmental policy support, and extensive farmer outreach programs are critical to overcoming the barriers to widespread adoption. With sustained innovation and practical implementation strategies, nanobubble fertigation holds the potential to revolutionize vegetable production systems by enhancing yields while conserving vital resources such as water and fertilizers

CONCLUSIONS

The study on DNFT highlights its significant potential in enhancing nutrient availability for cash crop vegetables, leading to improvements in productivity and quality. The integration of nanobubble technology in fertigation systems promotes better microbial activity and enhances soil biochemical processes, which in turn optimizes nutrient uptake by plants. This results in increased productivity up to 119% and consistent yield increments over time. From an economic perspective, DNFT offers substantial economic benefits through water and fertilizer savings, alongside higher yields, contributing to improved returns on investment. However, the adoption of this technology faces challenges, such as the lack of comprehensive cost-benefit analyses that consider capital investment, operational and maintenance costs, and long-term economic viability across diverse agricultural settings. Looking forward, the future perspective for DNFT in sustainable agriculture is promising,With ongoing innovation, stronger support systems, and broader awareness, it has the potential to revolutionize vegetable production by making it more productive, resource-efficient, and environmentally friendly.

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