Significance of aerated drip irrigation: a comprehensive review

Agricultural Water Management 321 (2025) 109886

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Significance of aerated drip irrigation: A comprehensive review

Hao Li [a], Abdul Rahim Junejo [a], David J. Midmore [b,*], Shakeel Ahmed Soomro [c]

[a] Institute of Farmland Irrigation Research, Chinese Academy of Agricultural Sciences, Xinxiang 453002, China
[b] School of Agriculture, Policy and Development, University of Reading, Whiteknights, Reading, RG6 6EU, UK
[c] Department of Farm Structures and Postharvest Engineering, Faculty of Agricultural Engineering and Technology, Sindh Agriculture University, Tandojam 70060, Pakistan

ARTICLE INFO

Handling Editor - Dr. Brent Clothier

Keywords:
Air compressors
Venturi injectors
Micro-nano bubble (MNB) generators
Fluidic oscillators
Hydrogen peroxide
Soil hypoxia

ABSTRACT

In recent years, aerated drip irrigation (ADI) has emerged as an innovative practice for efficient irrigation. It offers new approaches for the synchronized delivery of water and air, thereby enhancing the economic benefits of crops. Most previous studies have concentrated on the impact of imposed aeration within the irrigation stream on the soil environment and crop growth; increasing dissolved or soil air oxygen concentration in the root zone resulting in healthy root growth in otherwise unfavorable hypoxic soil conditions. However, the microbubbles (MBs) in irrigation water generated by aeration equipment serve multiple purposes. They are involved not only in the distribution of water and air through drip irrigation systems but also in the functional integrity of emitters and in altering the soil habitats in the crop root zone through various biochemical and biophysical mechanisms. Micro- and nano-bubble-mediated changes to the drip irrigation system and the soil microenvironment in the crop root zone have localized effects on microbial community aggregation, leading to significant ecological consequences. We outline the use of chemical gas filling (a weak solution of a peroxide directly into the rhizosphere) and mechanical gas filling devices (air compressors, venturi injectors, twin vortices, fluid oscillators, and micro-nano bubble (MNB) generators). This review emphasizes the role of ADI in improving crop growth, soil conditions, microbial populations and the management of emitter clogging in drip irrigation systems. Subsequently, we explore the key issues that need to be addressed in current ADI technology and discuss how micro- nano-bubble-induced alterations in the microenvironments of both the drip irrigation system, and the root zone soil can be harnessed. This approach can help manage and manipulate microbial communities, combat clogging in drip irrigation emitters, improve soil conditions for plant growth, and ultimately increase crop yields, resulting in a viable option for farmers world-wide.

1. Introduction

1.1. Background

Water scarcity has become a global concern, which with the passage of time will gain more attention and should seriously be managed (Janjua et al., 2021). Van Dijk et al. (2021) reported that with a sharp rise in population there will be a 35–56 % increase in the world's overall food demand between 2010 and 2050. In the agriculture sector, water is a crucial component needed to preserve agricultural productivity (Tang et al., 2024). A country's development strategy must include enhanced water productivity hand-in-hand with agricultural water conservation (Mujtaba et al., 2024). This is necessary to ensure food security (Molden, 2007) and modernize agriculture (Sanchis-Ibor et al., 2021).

When considering global food demand research, along with the impacts of anthropogenic climatic change (Sun et al., 2013), it has been inferred that the industrial sector's explosive growth and water demand are posing new challenges for irrigated agriculture (Taft, 2015). Traditional agricultural irrigation methods have become increasingly unable to meet the needs of modern agriculture. Playán and Mateos (2006) emphasized that the economic return on irrigation management is far higher than that of improving irrigation structures. Agricultural water saving is the inevitable choice for promoting the sustainable development of agriculture (Patle et al., 2020), by a) vigorously developing high-efficiency water-saving irrigation technology (Khan et al., 2021), b) proposing new methods for breaking through traditional models

* Corresponding author.
E-mail addresses: lihao01@caas.cn (H. Li), 2024Y90200013@caas.cn (A.R. Junejo), d.j.midmore@reading.ac.uk (D.J. Midmore), ssoomro@sau.edu.pk (S.A. Soomro).

https://doi.org/10.1016/j.agwat.2025.109886
Received 27 May 2025; Received in revised form 8 October 2025; Accepted 8 October 2025

(Tang et al., 2024), and c) marketing high-performance irrigation systems that use less water, all as crucial approaches to increase the effectiveness of water resources for agriculture (Levidow et al., 2014).

Therefore, it is necessary to respond to the pressing need for increased scientific and technological capacity to progress agricultural productivity, with an emphasis on improving water management practices. A key component of this review is a methodical investigation of aerated irrigation systems, which have the potential to impact the global irrigation industry and research environment by enhancing agricultural production, guaranteeing food security, and maintaining irrigation effectiveness and ecological sustainability.

1.2. The need for aerated drip irrigation (ADI)

Water conservation in agriculture now faces additional demands and difficulties due to the current state of agricultural development and due to the increasing demands on freshwater withdrawals by domestic and commercial users. Mueller et al. (2012) suggest that scientific management of water and fertilizer plays a key role in responding to food security and achieving sustainable development in agriculture. On the one hand it is argued that increasing water usage and creating high-efficiency water-saving technology can help mitigate the possible effects of future global climate change on agricultural development (Elliott et al., 2014). Yet on the other hand, Hongna et al. (2018) suggest that the current research goal on agriculturally efficient water management is insufficient to meet the needs of agricultural development. The latter propose that agricultural high-efficiency water is urgently needed to pursue fertilizer and water savings, market entry of water-saving products, and green ecology transformations. As a result, creating high-efficiency water-saving agriculture requires going beyond the single element approach and must fully utilize a variety of useful resources while integrating the growing environment for crops, their photosynthesis, water consumption, and farmland management to increase multi-element agricultural water efficiency in a synergistic way.

With irrigated agriculture, lack of soil oxygen is known to constrain root growth and activity (Gliński and Stępniewski, 2018) reducing the efficiency of crop water use (Dhungel et al., 2012). This phenomenon is particularly evident in fine-textured, clayey (heavy) soils characterized by slow drainage rates and slow recharge of soil air following irrigation (Drew and Lynch, 1980; Gliński and Stępniewski, 2018). Irrigation practices utilizing treated wastewater or saline water have been implicated in exacerbating oxygen deficiencies in the soil (Assouline and Narkis, 2013; Bhattarai et al., 2006). This is primarily attributed to oxygen demand of dissolved organic matter in wastewater, and the elevated irrigation volumes required for salt leaching. Additionally, elevated soil temperatures, exacerbated during the daytime, have been identified as another contributing factor to soil oxygen deficiencies (Crawford and Braendle, 1996; Asplund and Curtis, 2001; Ityel et al., 2014), as has the use of both plastic film mulch (Li et al., 2022) and organic mulching materials (Qian et al., 2022) that prevent air intake by the soil from the aerial environment.

Following a comprehensive examination of the effects of soil hypoxia and aeration on crop growth and development, numerous scholars have synthesized various strategies to improve soil water and gas dynamics where these were not optimal for root and crop growth. Examples include enhancing soil structure through deep tillage interventions (Abu-Hamdeh, 2003; Gomez and Garland, 2012), establishing artificial ventilation channels (Day et al., 1995; Qian et al., 2022), implementing judicious irrigation and drainage protocols (Van Lanen et al., 1992; Khan et al., 2002; Skiba and Ball, 2002; Scott and Renaud, 2015) including pulsed drip irrigation (Mohammadi et al., 2024) along with selection of crop varieties with tolerance to hypoxic soil conditions (Stepanova et al., 2002; Vartapetian et al., 2014).

Traditional sub-surface drip irrigation is prone to an exclusion of soil air (and consequently oxygen) around the root volume during and after irrigation events (Bhattarai et al., 2005; Qiao et al., 2023), causing an anaerobic environment in the root zone (Mahmoudi et al., 2022; Zhu et al., 2022), which reduces soil oxygen concentration (Zhou et al., 2022) and directly prevents aerobic respiration of the roots (Lei et al., 2024). The practice of aerated drip irrigation (ADI), this century's innovative approach, is an evolving water-saving method which aids in overcoming such oxygen-limited soil conditions. This method employs a combination of drip irrigation and aeration devices which optimize soil conditions for root growth, particularly during and immediately following drip irrigation when the wetted zone tends towards anoxia (Bhattarai et al., 2005). This technique delivers air, gaseous oxygen or oxygen-rich chemicals to the soil precisely. The methods carefully control fertilizer distribution, water management, and soil gas composition. The aerated irrigation method through multiple environmental modifications and growth factors significantly changes the root environment, resulting in marked increase in water use efficiency. Various studies have been conducted highlighting the efficiency of ADI in decreasing soil mechanical strength, increasing its soil aeration, soil air permeability and air-filled porosity (Baram et al., 2022; Niu et al., 2012; Zhu et al., 2016, 2019, 2020). These pivotal processes play crucial roles in alleviating soil hypoxia (Bhattarai et al., 2004, 2005, 2010; Friedman and Naftaliev, 2012; Wang et al., 2022), which results in an optimal environment for crop root development, maintaining crop metabolism, and optimizing water and nutrient use (Chen et al., 2018; Du et al., 2018; Pendergast et al., 2019). It has also been reported by numerous authors that this method results in better water conservation and increased production (Cui et al., 2020a; Liu et al., 2019; Pendergast et al., 2013; Wu et al., 2019). Indeed, although Fan et al. (2021b) report that aeration increases the emitter flow rate, Sun et al. (2024) show that the irrigation flow rate decreases with increased air ratio in the irrigation water, as did one or our studies (Figure 6b in Torabi et al., 2013) and the addition of air or oxygen as bubbles to the irrigation stream reduces proportionately the amount of water delivered per unit time given a constant pressure (for example a venturi device can draw about 12–15 % by volume of water (e.g., Bhattarai et al., 2013)) and contribute to the air void fraction, leading to an often overlooked improvement in water use efficiency.

Thus, ADI technology emerges as an important solution for reducing crop rhizosphere hypoxia, offering an optimal method for precise dissemination of water, nutrients and gases within the crop root zone. This innovative method not only helps to achieve respectable yields, but also catalyzes substantial research investments, advancing the drip irrigation methodologies.

2. The status of aerated drip irrigation

Notably, the regulation of soil water and gas environments within the crop root zone through subsurface drip irrigation has attracted considerable research attention. This includes active aeration of the root zone by forcing air or oxygen directly through the irrigation infrastructure, generally after an irrigation event, or by more passive methods using the same drip irrigation network to transport a water-gas mixture medium to the soil during, or close to the end of, irrigation. Termed loosely herein as "aerated drip irrigation," these methods represent a novel approach to optimizing the soil environment conducive to enhanced crop productivity. In the pursuit of optimizing water and gas irrigation efficiency, the selection of suitable gas filling techniques and equipment emerges as a pivotal determinant. Currently, within the domain of drip irrigation systems, prevalent gas irrigation methodologies encompass chemical gas filling and mechanical gas filling.

2.1. Gas filling methods and gas filling equipment

2.1.1. Chemical gas filling

Chemical gas filling entails the generation of gaseous oxygen resulting from a given peroxide's inherent chemical instability, readily decomposing to generate oxygen within the irrigation stream and/or the soil.

This methodology involves administering an aqueous solution of a peroxide directly into the irrigation stream and subsequently to the crop root zone, thereby augmenting the soil oxygen concentration in proximity to the roots. Commonly employed peroxides in chemical filling methodologies include fast oxygen release compounds such as hydrogen peroxide (H_2O_2), urea peroxide ($CH_6N_2O_3(NH_2)_2CO{\cdot}H_2O_2$) and potassium peroxide (K_2O_2) and slow oxygen release compounds such as calcium peroxide (CaO_2) and magnesium peroxide (MgO_2) (Bryce et al., 1982; Ben-Noah and Friedman, 2016b; Hou et al., 2021; Thani et al., 2016). Quite recently, Thomas et al., (2025) have studied various formulations of low concentration (10 ppm) H_2O_2 with differing stabilities in drip irrigation, directed at capitalizing on the oxidizing effect of H_2O_2 reducing emitter blockage and on release of oxygen into the irrigation stream.

Hydrogen peroxide was initially utilized in an agricultural context for seed sterilization (Massee, 1913). In the early 1940s, the Illinois Agricultural Test Station, under the direction of Melsted, conducted field experiments to investigate the effects of irrigating corn and soybean crops with 1000 ppm hydrogen peroxide solutions in the soil root zone. Yields of maize and soyabean in a well-structured soil were, respectively, 48 % and 7 % greater compared to irrigation with water alone. This affirmed the efficiency of the chemical filling method (Melsted et al., 1949). Later, Bryce showed that urea peroxide (4 mL L^{-1}) alleviated short-term flooding stress in pots with a 20 % tomato yield advantage over the flooded control (Bryce et al., 1982). Bhattarai et al. (2004) supplied H_2O_2 at 5 L ha^{-1} in the irrigation stream through emitters for 25 min after flooding of a heavy clay soil in the field, on four weekly occasions, and increased yield of zucchini by 25 %. And the benefit of irrigation with H_2O_2 was also evident with a tree crop, as demonstrated by Gil et al. (2009) for avocado in 200 L containers with a heavy clay loam soil, with a marked 27 % gain in aboveground biomass. In simulated field conditions, irrigation of corn (*Zea mays*) and coriander (*Coriandrum sativum* L.) with 10 and 100 ppm of H_2O_2 led to greater release of oxygen and considerably greater growth and yield benefits on a ferrosol compared to a vertosol, than at the higher concentration (1000 ppm) of H_2O_2 (Thomas, 2021). In line with this lack of benefit at higher concentration of H_2O_2, Ben-Noah and Friedman, (2016b) supplied H_2O_2 at 600 and 800 ppm to *Capsicum annuum* plants growing on a vertisol, with no beneficial effect on yields. However, for wheat yield, benefit was optimal at 800 ppm, superior to that at either higher or lower concentrations (Wang et al., 2024b).

Nevertheless, despite these mostly positive documented effects of delivery of hydrogen H_2O_2 in irrigation streams, confirmatory publications are lacking.

As an aside, in addition to delivery of peroxides through the irrigation stream, solid peroxide compounds, applied as a basal fertilizer directly to the soil, have been successfully employed to enhance dissolved soil oxygen, for example with calcium peroxide in rice cultivation (Hou et al., 2021).

2.1.2. Mechanical gas filling

The term mechanical gas filling describes the processes of either (a) direct delivery of compressed air through the irrigation infrastructure, or (b) the creation and maintenance of small bubbles containing air or pure oxygen within the drip irrigation pipe network and delivery of that super-aerated/oxygenated irrigation water to the crop root zone by mechanical means. Air compressors, venturi injectors, mix-aerators, fluidic oscillators and micro-nano bubble (MNB) generators are most commonly used.

2.1.2.1. Air compressors. Research conducted in the last few decades has shown that forced pressurized aeration of irrigation infrastructure has some favorable effects on crop yield and quality, overcoming hypoxic stress which otherwise has a negative impact on root and soil microbial activities (Yuan et al., 2016). Early in the 1980s, Busscher discovered that using an air compressor (e.g., as in Fig. 1(a)) to forcibly aerate the root zone at 10 cm below the soil surface regulated at 15 kPa (2 psi), through a perforated tube for varying periods after watering by flooding, significantly boosted the yield of eggplant, tomato and pepper (Busscher, 1982). Subsequently, Niu et al. (2012) employed a similar methodology to investigate the effects of a 5 min period of forced injection of air through a subsurface irrigation system following irrigation, on soil air permeability of soils with differing bulk densities. The soil air permeability was increased by from 3.0 to 3.7 times depending upon soil type at the lowest bulk density, and equaled that immediately prior to irrigation. Other studies (Ben-Noah and Friedman, 2016a) showed that direct injection of air via 40 cm deep subsurface drippers improved soil oxygen concentration in soil air, and yield, but only in soils with a constantly high (>0.4) volumetric water content. Indeed, the yield of pepper at lower water contents was reduced by such forced aeration. Enclosing the dippers with a perforated 10 cm diameter polypropylene sphere resulted in significant increases of soil oxygen concentration, most likely due to enhanced air spread in the soil compared to the ‘chimney effect’ of direct air injection without the sphere (Ben-Noah and Friedman, 2016a).

Besides direct delivery of compressed air in the absence of irrigation water through the drip infrastructure, compressed air has been injected directly into the irrigation stream to achieve c. 12 % air by volume (Abuarab et al., 2013), with notable increases in maize yield, and likewise pure compressed oxygen delivered through a small-pore diffuser into the irrigation stream (Bonachela et al., 2010).

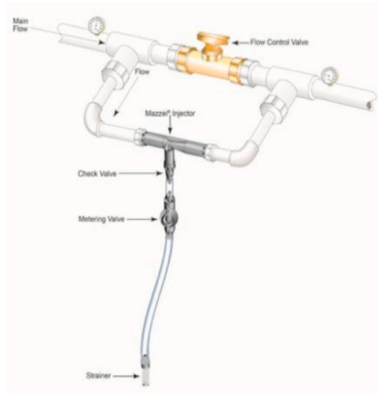
A representative example of a setup for mechanical gas filling is illustrated in Fig. 2.

2.1.2.2. Bubble sizes. Since all the following practices for aeration of the irrigation stream create bubbles, a digression on bubble characteristics and size is in order here before the actual mechanisms are discussed, although definitive standards on size are still lacking Among the various definitions of bubble size, for example, micro-bubbles are defined as bubbles of less than 50 μm in diameter by Takahashi et al. (2003) and Takahashi (2005), although others (e.g., He et al., 2023) generally recognise MBs as being from 10 up to 100 μm. The smallest bubbles produced by venturis, twin vortex and fluidic oscillators are reportedly micro in size. Nanobubbles (NBs), have been defined with diameters smaller than 1000 nm (Favvas et al., 2021), and MBs smaller than 4 μm are produced in unison with nanobubbles by commercial micro-nano bubble (MNB) generators (Ahmadi and Khodadadi Darban, 2013), both sizes with negligible buoyancy (Arwadi et al., 2023) and little tendency to rise and coalesce. Small-sized bubbles are preferred to larger sized bubbles in ADI, for the former, especially micro and nano bubbles (MNB), have a slower ascent rate than larger bubbles, and smaller bubbles have a greater oxygen transfer efficiency, a higher dissolved oxygen peak and up to 16 times longer durability than larger bubbles (Li et al., 2014). In addition, Khan et al. (2020) reported that MNB possess additional special qualities such as strong oxidation potential, high surface area, and long-lasting stability, and range in size from nanometers to micrometers. Sakr et al. (2022) highlighted that the MNB small size, typically less than 10–15 μm, increases their gas dissolution rate in water, causing a supersaturated state when compared to macro bubbles (typically 600–2500 μm). Hence attention has been turned to the use of even smaller, NBs, as a means of enhancing the delivery of air and oxygen to the root system though the practice of drip irrigation.

2.1.2.3. Venturi injectors. During this century, significant advancements have been made in mechanical gas-filling drip irrigation technologies. Among these advancements, the integration of venturi so called ‘injectors’ (Fig. 1(b)) into drip irrigation systems emerged as one of the foremost methods for mechanical gas filling (Fig. 3(a)). In a drip

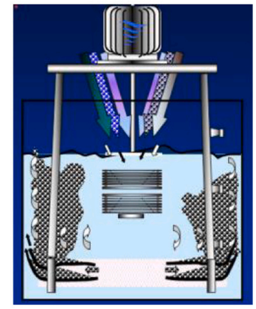
(a) air compressor

Issu.com

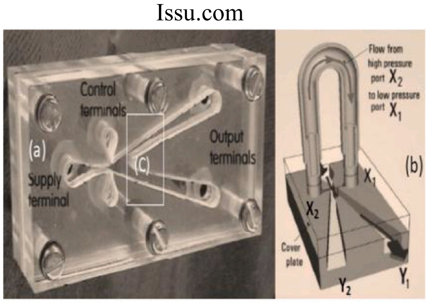


(b) venturi injector

mazzei.net



(c) mixaerator from https://newatlas.com/mixaerator-sterilise water-without-chemicals/3411/



(d) Fluidic oscillator from Rehman et al. (2015)

(e) micro-nano-bubble generator

aquab.com

Fig. 1. Mechanical gas filling devices.

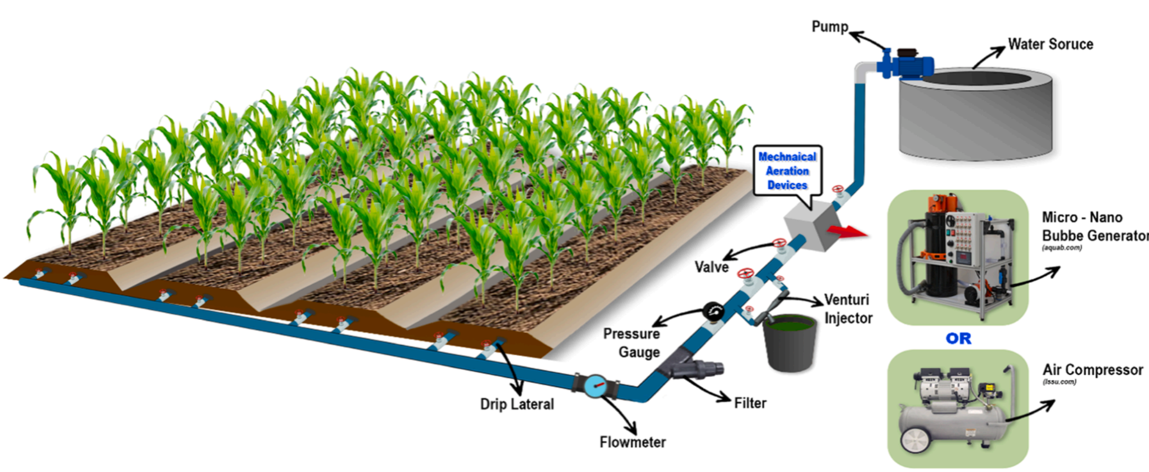


Fig. 2. Schematic diagram of the aerated drip irrigation system.

pipe network, the pressurized irrigation water creates a high-speed jet at the venturi jet nozzle, generating a local vacuum at the throat tube. This vacuum draws external air, or oxygen if so delivered, through the suction port (Fig. 3(b)) into the venturi injector due to an external pressure difference, in the same manner that fertilizers in solution are often introduced into the irrigation stream. Turbulent shear is created

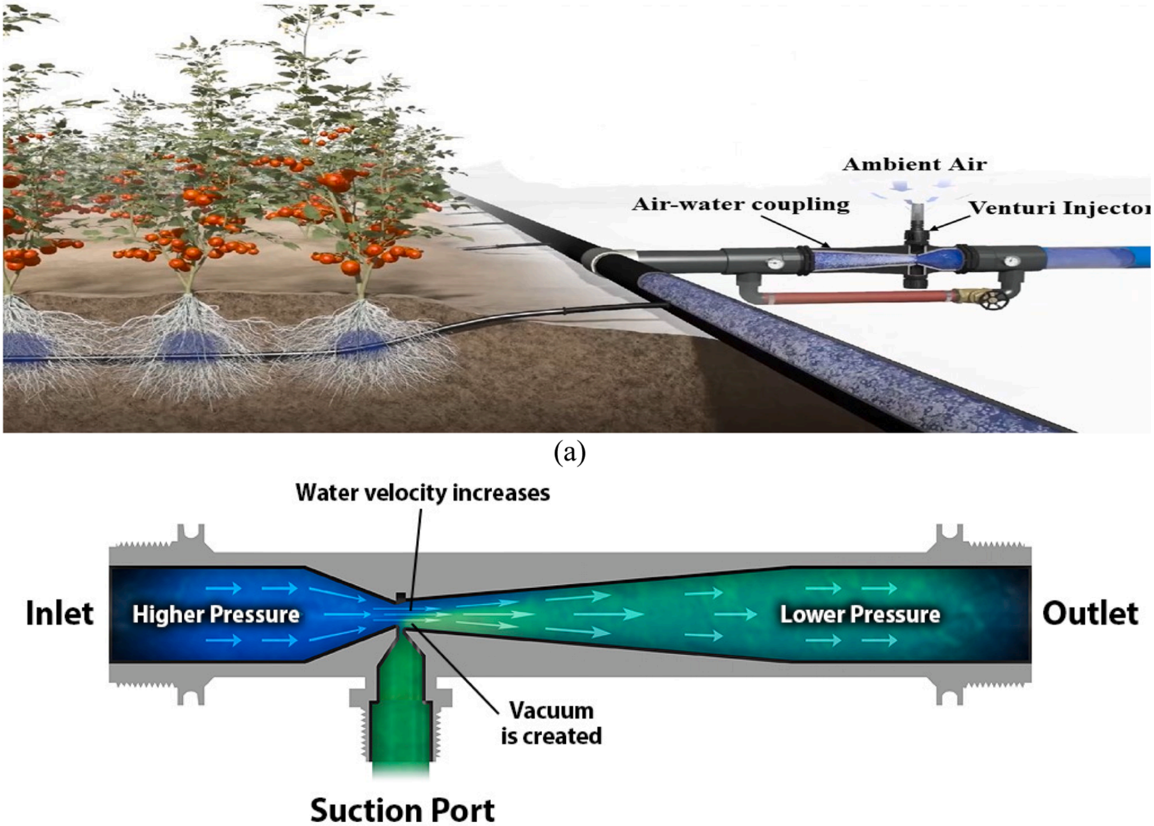


Fig. 3. Schematic diagram of (a) venturi injector aerated drip irrigation system in the field and (b) internal structure of a venturi with flow and pressure variations. Bypass pressure valves and gauges make it simple to achieve the necessary aeration rate. A larger pressure differential will create a more powerful vacuum and greater suction of air. (https://mazzei.net/products/venturi-injectors/) and (https://www.irrigationking.com/help/irrigation-articles/venturi-fertilizer-injectors/).

within the high-speed water flow and numerous micro bubbles (e.g., measured from 10 to 20 μm upwards in diameter) to large lumps of air bigger than 100 μm are formed (Bhattarai et al., 2013), thoroughly mixing with the irrigation water. Introduced by the Mazzei Corporation, USA, the pioneer behind the "AirJection" venturi injector for drip irrigation systems, this company has continued to be a manufacturer of choice for venturi technology with continued agricultural applications such as referred to by Chen et al. (2011) and Essah and Holm (2020). The Mazzei air injector Model 384, when creating a pressure differential operating at an inlet pressure of 386–393 kPa and an outlet pressure of 110–130 kPa, draws in about 12–15 % air by volume of water (Bhattarai et al., 2013). This results in a water and gas (usually air, but if so arranged, pure oxygen) mixture with an above-natural dissolved oxygen concentration (e.g., >6. vs c. 4 mg L^{-1} in a control (Lei et al., 2016)), or even higher for example 8 mg L^{-1} in the control, 15 mg L^{-1} with venturi aeration and 38 mg $L^{-1}$with oxygen delivery through the venturi (Lei et al., 2020), the control values depending on atmospheric pressure and temperature. The venturi injector operates solely on pipe hydraulic forces, eliminating the need for additional power devices. Furthermore, due to its compact design, straightforward structure, and ease of installation and maintenance, the venturi injector has found extensive application in engineering design. Consequently, it has increasingly become the preferred focus of scholarly agricultural research aimed at understanding the response patterns of crop habitats through gas-filled drip irrigation (e.g., Goorahoo et al., 2002; Bhattarai et al., 2004, 2006; Zhang et al., 2019).

A variation of the venturi system (Seair Venturi Diffusion System, Model SA75) has also been used experimentally, for example by Lei et al. (2020) – in the absence of crops), and Chen et al. (2011) – wheat).

2.1.2.4. Vortices. A rotating flow caused by an external stirring device within a fluid vortex creates a greater velocity and a decreased pressure closer to its centre and this creates a suction effect. Using the principle of a twin vortex (Fig. 1(c)), and their high suction effect of infused air, a commercial application has been successfully used in agricultural contexts with inline units named ‘Oxysolver” for the mixing, aerating, and pumping of irrigation water (Bhattarai et al., 2005). Research with the use of the units in Australia has shown yield increases in the range of 15–35 % in moderately waterlogged soils. In addition, a similar system using a multistage vortex aerator (Ghosh et al., 2023) fed with pure oxygen has also been successfully employed to raise dissolved oxygen concentration from c. 1 mg L^{-1} to c. 7 mg L^{-1} in wastewater.

2.1.2.5. Fluidic oscillator. The beauty of a fluidic oscillator to generate MBs is, as for a venturi aerator, that it works independent of an energy source, using the stream of irrigation water as the driving force. As with venturi injectors, fluidic oscillators have no moving parts (Fig. 1(d)). The unit comprises two components, an amplifier forming a specially designed cavity, and a feedback loop that diverts the input jet from side to side in the cavity, through the feedback loop (Rehman et al., 2015). Bubble sizes range from 80 to 450 μm, with the majority ranging from 80 to 120 μm (Rehman et al., 2015), although when used with compressed air and 20 μm pore size diffuser stones Lei et al. (2016) refer to bubbles having an average size of 20 μm.

According to Tesař (2024), the fluid’s characteristics, the oscillator’s geometry, and the fluid mass flow rate all affect size of bubbles produced by the fluidic oscillator, and can be controlled through modifying the operating parameters, including the oscillator pressure differential and flow rate.

2.1.2.6. Micro-nano bubble generators. In recent years, researchers have identified MNB technology as an innovative development situated at the intersection of water science and nanotechnology. Micro-nano bubble generators, due to their wide applicability in biology, environmental science, medicine, agriculture, and fisheries, have gained significant practical attention (Lyu et al., 2019; Chirwa et al., 2024) and several studies highlight the physical, biological, and chemical characteristics of MNBs (Atkinson et al., 2019; Zhang et al., 2020; Zhang et al., 2023).

There are several methods for producing MNBs (summarized by Arwadi et al., 2023; Favvas et al., 2021) including mechanical methods (e.g., fluidic oscillators and hydrodynamic cavitation, although the former is more speculative than real), chemical methods, and optical and electrical methods, of which the mechanical methods are those most commonly used for production of bulk nano bubbles in wastewater treatments and in research on use of MNBs for irrigation. The schematic diagram of a MNB generator is provided (Fig. 1(e)), while the process of MNB aeration is further provided in Fig. 4.

Notably, surface charges from MNBs cause potential differences that impact the adsorption of suspended particles in irrigation water (Xiao et al., 2020) by producing radicals that aid in the degradation of organic matter within the irrigation water and thus mitigate biofouling. This is also important in the co-development of fertilization and aeration, which, due to the negatively charged surface of the bubbles, increases the efficiency of nutrient absorption by plant roots (Park et al., 2010). Consequently, MNBs are particularly suitable for the synchronous transmission of water and gas through the drip irrigation pipe network, not only increasing crop yield and quality but also contributing, through improved nutrient transport into plant roots due to high mass diffusion rates,and to reduced environmental impacts associated with the use of chemical fertilizers (Ahmed et al., 2018).

As research on gas filling drip irrigation continues to advance, this technology has increasingly become a focal point in the realms of water-saving irrigation and for enhancing crop value-added production. Diverse aeration methods yield distinct effects on crops. Studies suggest that the chemical aerated method and NBs facilitate the absorption of soil nutrients by crops (Ahmed et al., 2018), whereas mechanical filling methods can additionally bolster root vitality, thereby promoting the growth of plant root systems (Li et al., 2015; Zhao et al., 2023; Yu et al., 2024).

Comparisons of the effectiveness of the various technologies to aerate irrigation water are scarce, but one study (Wang et al., 2023c) reports on the limitation of mechanical (air forced through air stones) and venturi aeration imposed by the saturated dissolved oxygen concentration of irrigation water, reaching on average 9.13 and 9.12 mg L^{-1}, respectively, compared to 3.95 mg L^{-1}, in the non-oxygenated groundwater used in the control. Chemical gas filling, with various concentrations of sodium percarbonate which decomposes to oxygen and sodium carbonate, although it was slower to complete the reaction leading to oxygen evolution, reached a much higher maximum value of 30.5 mg O_2 L^{-1} water. And in a comparison of a prototype fluidic oscillator and a venturi (Lei et al., 2016), induced aeration with the fluidic oscillator maintained a longer duration of elevated dissolved oxygen in the water by a factor of two compared to the venturi aeration, despite the venturi resulting in a greater increase in the air fraction compared to the fluidic oscillator.

Once the oxygenated irrigation water reached the soil, there was no difference between treatments in the pattern of dissolved oxygen concentration over time, first a slight decrease, and then an increase proportional to the oxygen concentration in the irrigation water (Wang et al., 2023c).

2.2. *Impacts of gas filling on the soil environment, particularly microbial activities*

Good soil quality is pivotal for ensuring food security, water security, and ecological stability (Pozza and Field, 2020). However, agricultural practices and natural phenomena induce changes in soil integrity, affecting its quality. Practices that subject the root zone temporarily to reduced oxygen levels, such as irrigation, flooding and soil compaction compromise crop health. Low-oxygen stress impedes root respiration, microbial activity, and overall crop vitality (Asplund and Curtis, 2001; Assouline and Narkis, 2013; Friedman and Naftaliev, 2012; Ityel et al., 2014). Therefore, addressing soil aeration in the root zone emerges as a crucial strategy to optimize crop growth and bolster soil productivity. The aforementioned gas filling methods are expected to impact on soil function, physical, chemical and biological, for the benefit of crop production.

Aerated irrigation has significant effects on the soil water and gas environment (Chen et al., 2019). Research showed a significant 16.6 % increase in soil oxygen concentration when venturi gas filling was used, along with a significant 4.5 % decrease in soil moisture content (Zhu et al., 2016). Furthermore, this intervention corresponded to a

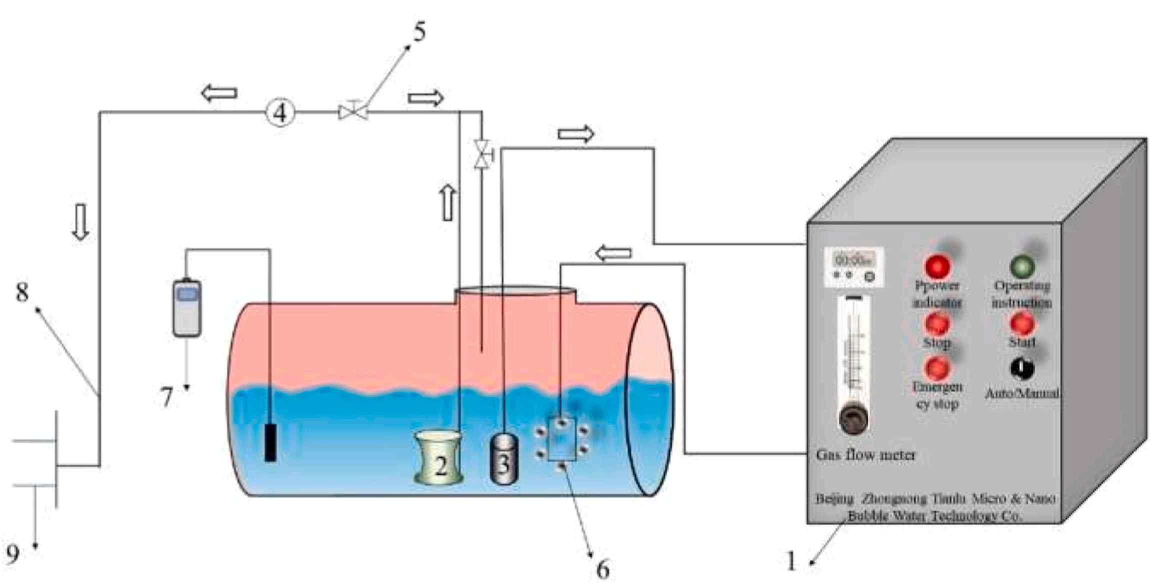


Fig. 4. Schematic diagram of MNB Aeration. Note: The arrow in the figure indicates the direction of water flow, and the meaning of the number is 1: Micro- Nano-Bubble Generator; 2: Submersible pump; 3: Bottom valve; 4: Water meter; 5: Water control valve; 6: Aeration head; 7: Oxygen meter; 8: Water pipe; 9: Drip pipe. Adapted from Ma et al. (2025).

significant 33.2 % rise in soil respiration rate. Similarly, studies by Sang et al. (2018) demonstrated the efficiency of MNB aeration for early rice, by Zhu et al. (2012) with a micro-bubbler during the late rice grain filling stage and by Hu et al. (2017) with micro-bubbles throughout a paddy rice crop cycle in mitigating rhizosphere hypoxia induced by prolonged soil inundation. Dhungel et al. (2012) reported that this technique not only optimized soil aeration status but also enriched soil microbial diversity, consequently promoting increased pineapple yields. Here we focus on effects of gas filling on microbial activities, given their sensitivity to variations in soil aeration.

The activity of soil microbial communities is closely linked to soil enzyme function, which is a significant indicator when relating soil quality and fertility, and crop growth status. Various authors, e.g., Heuberger et al. (2001) and Li et al. (2016) using forced air injection through the irrigation system, either following irrigation or every two or four days, and Brzezinska et al. (2001) modifying soil aeration conditions through different degrees of compaction, observed a correlation between soil enzyme activity and soil aeration, underscoring the positive impact of enhanced soil aeration on key soil enzymes e.g., catalase and dehydrogenase. In addition, MNB aeration raised alkaline phosphatase activity by 15 % and available phosphorus by 21 % in the maize rhizosphere by increasing the diversity of bacteria and complexity of fungi networks, which favored phosphorus availability of the soil (Bian et al., 2025). Similarly, Wei et al. (2025) found that ADI coupled with organic fertilizer increased yield and quality of *Panex notoginseng* by improving the soil microenvironment, particularly the soil water content and catalase and urease activities, and soil bacterial and actinomycete populations. This underpins how crucial soil aeration is for promoting enzymatic activities that are critical for the cycling of nutrients and the general health of the soil.

The diversity of soil microorganisms and their biomass and biological activities are intricately intertwined with soil formation and its development, as they decompose and transform organic matter and soil nutrients (Jacobsen and Hjelmsø, 2014). The activity of the soil microbial community enhances crop nutrient uptake, improves root structure (e.g., Jin et al., 2023), and fortifies crops against biotic and abiotic stresses. Consequently, the water and gas environment with aerated irrigation being created in the crop root zone is favorable for the proliferation of soil microorganisms, enhancing their activities as discussed below.

When adopting an underground drip irrigation network with forced air soil aeration, a significant increase occurred in abundance of bacteria, fungi and actinomycetes in the tomato root zone (Li et al., 2016), and likewise with the use of a venturi (Lei et al., 2022). Zhao et al. (2017) investigated the impact of forced air on soil chemical properties and the bacterial community structure in the root zone using high-throughput genome sequencing. Adding air directly to the root zone significantly improved the important functional soil bacterial communities. Specifically, gas filling enhanced the number of *Pseudomonas* and *Bacillus* with metabolic functions related to phosphorus and potassium absorption via decomposition of organic matter. Other studies with H_2O_2 delivered in the irrigation water (Thomas et al., 2025) showed that microbial biomass was reduced, but microbial diversity was unaffected. In contrast, even though the activity of crop rhizosphere enzymes was enhanced with venturi enhanced oxygen concentration of 15 vs. 5 mg L^{-1} in the irrigation stream, the diversity of soil microbial communities decreased with the increased oxygen concentration (Lei et al., 2022), implying the need to study long-term the impacts of oxygenated irrigation on soil ecology. Yet other studies (Rao et al., 2018) showed that chemical based (calcium peroxide) supply of oxygen in the irrigation stream increased both soil bacterial population and biomass by 21 % compared to a check, but less than the 28 % increase by a physical based (microbubble) aeration. In line with these results, Zhu et al. (2024) have shown that increasing the concentration of dissolved oxygen to 15 mg L^{-1} in aerated irrigation water, altered life history strategies of soil microorganisms contributing to the regulation of C cycling, and enhanced the fixation of inorganic carbon and raised soil organic carbon content, as too have Qian et al. (2022) for C and N cycling.

Of note, Wang et al., (2025a) reported that micro-nano bubble hydrogen water subsurface drip irrigation was effective in alleviating salt stress on lettuce growth and photosynthesis through the promotion of root, antioxidant, and osmotic balance development. This practice also reduced stress hormones (abscisic and jasmonic acids) and enhanced useful plant growth promoting rhizobacteria in the soil that enhance IAA synthesis and diminish growth inhibition via ethylene. However, when exposed to no stress factors, surplus dissolved hydrogen may inhibit the growth of roots because of a decrease in dissolved soil oxygen.

Soil nitrification and denitrification bacterial activities are largely controlled by the amount of oxygen present in the soil (Chen et al., 2019). Therefore, alterations in soil nitrification and denitrification processes by aerated irrigation have an impact on the functional state of nitrogen in the soil and on the generation and release of soil greenhouse gases, such as carbon dioxide (CO_2) and nitrous oxide (N_2O). Several studies have emphasized the effect of aerated irrigation on emissions of greenhouse gases. Chen et al. (2018) showed that venturi-based soil aeration enhanced N_2O emissions significantly in one of two seasons trialled. The authors related this to greater concurrent aerobic and anaerobic sites in the soil in the year with greater emissions, causing a continuous coupling of denitrification and nitrification with enhanced N_2O emissions.The same venturi treatment increased average soil CO_2 emission and reduced CH_4 emissions for greenhouse tomato production, with a decrease in net greenhouse gas intensity (i.e., the ratio of net global warming potential to tomato yield) but the differences between aeration and no aeration were not significant. Hou et al. (2016) reported similar effects with venturi aeration of the irrigation stream, and although N_2O emissions were somewhat higher with aerated irrigation, the difference was not significant. Both studies showed that with venturi aerated irrigation there were negligible effects on the global warming potential. Likewise, Oo et al. (2018) using NBs on a well aerated andosol recorded a nonsignificant increase in N_2O with aerated compared to nonaerated irrigation soon after fertilizer application, which was however obviated with the addition of biochar, and Zhang et al. (2019) using venturi aeration found, again, non-significant increases in CO_2 and N_2O emissions, with such increases likely related to changes in soil microbial populations and activities induced by aerated irrigation. In the study by Zhao et al. (2017), gas filling promoted the number of nitrobacterium bacteria with nitrification functions, concurrently inhibiting denitrifying bacteria. Likewise, venturi based aerated irrigation water in the crop root zone enhanced soil nitrification while decreasing soil denitrification, thereby improving soil fertility (Chen et al., 2021) and through venturi aeration facilitating crop absorption of nitrogen (Cui et al., 2020b). Of interest, in laboratory studies use of solid calcium peroxide or magnesium peroxide reduced N_2O production under hypoxic condition soil conditions, but a concomitant reduction in microbial biomass was also evident (Bera et al., 2020), and a study by Baram et al. (2021) showed that delivery of oxygen NBs in a surface irrigated lysimeter study reduced N_2O production by 37 %.

The apparent inconsistencies in reported N_2O responses to aerated irrigation, even though they were almost all non-significant when compared to no aeration, likely stem from variations in experimental context and methodological approaches. Soil type is a critical determinant, as differences in texture, organic matter content, and baseline aeration status influence oxygen diffusion and thus microbial nitrification–denitrification dynamics. For instance, microbial populations in fine-textured or poorly drained soils may respond differently to added oxygen than coarse-textured soils with inherently higher porosity. However, when we reviewed the soil types in the reported studies on N_2O generation which ranged from silty clay loams to andosols and a brown soil, other than in the study by Baram et al. (2021), where the aeration reduced N_2O very significantly (most likely related to the high ammonium and nitrate concentration in the treated waste water and the very poorly aerated soil conditions, that would likely favour much denitrification in the absence of aeration), we could not relate the effect of ADI on N_2O emission to soil type. In addition, the method of aeration plays a decisive role: venturi injectors typically generate larger bubbles with limited persistence in the soil solution, whereas micro- or nano-bubble systems provide more stable oxygen delivery, potentially altering microbial pathways in distinct ways. Seasonal and climatic factors also modulate responses, since temperature and soil moisture strongly regulate microbial activity and greenhouse gas fluxes. Furthermore, differences in experimental scale (pot, lysimeter, or field trials) and crop type can affect root exudation patterns and rhizosphere microbial communities, contributing to divergent outcomes. Taken together, these factors underscore the need for context-specific evaluation of aerated irrigation, as its impact on N_2O emissions cannot be generalized across soil and management conditions. Such intricate relationships between soil gas filling, microbial activity, and greenhouse gas dynamics, emphasize the importance of holistic long-term approaches to agricultural management that consider both productivity and environmental sustainability.

Aerated irrigation orchestrates a comprehensive regulation of the root growth environment, seamlessly optimizing the efficiency of water, fertilizer, gas, heat, and other pivotal factors essential for farmland productivity. The aerated irrigation method, by refining and optimizing soil water and gas conditions, serves as a catalyst for microbial proliferation, and stimulation of functional soil respiration. Adoption of ADI, besides improving the physical and chemical qualities of the soil, also effectively deals with the inherent soil water and gas paradox within the root zone.

2.3. Effect of gas filling on root, canopy and yield characteristics and water use efficiency

2.3.1. Roots

Root system vitality directly affects crop nutrient absorption and water use efficiency, playing a key role in various physiological processes critical to crop development (Smith and De Smet, 2012). The oxygen concentration within the soil in the crop root zone constitutes a critical environmental factor, exerting a profound influence on the morphological structure of the crop root system (Jin et al., 2023) and on the abovementioned metabolic function of various bacteria (Hashmat et al., 2024). Therefore, the impact of ADI on the soil environment directly influences the functional strength of the crop root system and is intricately linked to the healthy growth of crops.

Consequently, various authors such as Baram et al. (2022) supplementing the crop root volume with NB-oxygenated waste water and Lei et al. (2023) with venturi aeration found that these aeration treatments effectively enhance the vitality of crop roots, improve the absorptive capacity of water and nutrients per se and through the action of root endophytic bacteria (Wang et al., 2023b) consequently improving to varying degrees crop yield. Cui et al. (2020a) showed that venturi aeration could well improve various parameters of cucumber root growth –, fresh root weight, root dry weight, root length – leading to greater yield and net income. Likewise, Zhang et al. (2022) with a patented cycle aeration device, showed similar aeration benefits on the total root length, surface area, volume, and root activity, the latter as determined by the Triphenyl Tetrazolium Chloride test.

Many studies have established that gas filling can effectively promote water, fertilizer, and gas coordinated regulation of crop growth, strengthening the absorption of soil nutrients (Bhattarai et al., 2004; Niu et al., 2012; Li et al., 2016; Sang et al., 2018; Pendergast et al., 2019; Zhu et al., 2020), stimulating the vitality of the crop root system (Assouline and Narkis, 2013; Chen et al., 2019; Wang et al., 2023b; Zhao et al., 2017), encouraging healthy growth and development of crops, improving crop yield and where relevant quality, and enhancing the economics of crop production.

2.3.2. Canopy parameters and yield

Pendergast et al. (2013) reported that ADI, besides enhancing root development, also increased light interception by the cotton canopy and improved yield and water use efficiency. After statistical analysis of seven years of venturi aerated drip irrigation, they found that cotton production was increased by 10 % and irrigation water utilization efficiency by 7 %. Their experiments on greenhouse vegetables (Bhattarai et al., 2008) also showed that venturi ADI increased water utilization efficiency, stimulated leaf transpiration rate and increased harvested yield of soybean, chickpea, and pumpkin production by 43 %, 11 %, and 15 %, respectively. Bhattarai et al. (2006) using venturi aeration related this phenomenon to the gas filling which increased the soil oxygen concentration, effectively overcoming the aforementioned unfavorable effects of heavy clay hypoxia on root function and crop growth. They showed that ADI in heavy clay increased the fresh weight of tomatoes by 21 % and water utilization efficiency by 11 %, whereas in saline soil, drip irrigation increased tomato fresh weight by 38 % and season long water utilization efficiency of fruit by 77 %. Likewise, according to Dhungel et al. (2012) venturi ADI enhanced pineapple growth, quality, instantaneous water utilization efficiency (μmol CO_2 assimilated for each mmol of H_2O transpired) and yield. Some early studies by Goorahoo et al. (2007) from California State University, USA, employing the venturi drip irrigation method, investigated the effects of ADI on the yield of three crop species: sweet pepper, melon, and cantaloupe and showed a significant improvement in yield mainly due to increases in fruit numbers. More specifically, they reported promising yield increases of between 16 % and 39 % resulting from increases in fruit number of between 13 % and 33 %. Furthermore, Wu et al. (2022) using venturi aeration reported that ADI led to a significant increase in maize yield under both degradable and plastic mulching films.

The results of Li et al., (2022), Ouyang et al. (2021). and Zhang et al. (2022) also showed that adding MNBs to drip irrigation not only improved tomato plant height, stem thickness and yield, but also enhanced the content of tomato organic acid and vitamins and fruit hardness, which effectively improved the quality of tomato and their flavor. The positive impact of various ADI practices on output and fruit quality was also consistently confirmed using a micro-nano bubbler by the investigations of Liu et al. (2019) for tomato, by Wang et al. (2022) for capsicum and Wang et al. (2023a) for strawberry. Likewise, use of nano air bubbles for irrigation of tomatoes improved harvest quality and increased agronomic nitrogen uptake efficiency, water use efficiency, earliness and size per fruit, being more efficient than with nano oxygen bubbles (Del Moral Torres et al., 2024). However, total and marketable yields with both were also increased but not significantly so, although the authors do not suggest reasons for this lack of total yield benefit. In contrast, increases of soil oxygen had positive impacts on strawberry yield and quality, and soil fertility, when air-MNBs were introduced to the irrigation stream (Wang et al., 2023a). Furthermore, studies on melons conducted by He et al. (2022), on cucumber by Ouyang et al. (2023) and on water melon by Zhou et al. (2023) support the notion that ADI with a MNB generator can boost yield and quality while also enhancing the financial advantage.

A limited number of yield comparisons between the use of chemical and mechanical gas filling would suggest neither practice is uniformly superior to the other in improving yield under field conditions. For example, Hu et al. (2017) reported a c. 9 % greater yield with chemical gas filling than mechanical gas filling, and the latter was itself superior to the control by 11 %., which is in line with the greater dissolved oxygen concentration with chemical gas filling noted earlier in those studies. However, in a pot trial comparison, with equivalent increases in supply of oxygen to the root system via subsurface drip irrigation, venturi aeration was slightly more effective than H_2O_2 at improving cotton yield, but in contrast with vegetable soybean no difference in yields between aeration treatments was noted; for both crops treated yields were significantly higher yielding that the control (Bhattarai et al., 2004). And in a field study by Rao et al. (2018) with cotton, both chemical and mechanical gas filling increased yield significantly, by c. 11 % compared to the control, emphasising benefits of aeration treatments on crop yields.

2.3.3. Water Use Efficiency

The benefits of ADI and its involvement in improving WUE have been noted and reported by numerous research scholars. Research by Gil et al. (2009) revealed that injection of H_2O_2 contributed to gains in above-ground biomass (27 %) and WUE (17 %) of avocado on a heavy clay loam soil. Similarly, Zhou et al. (2022) working with tomato and various NB dissolved oxygen concentrations reported a range of improvements of irrigation water use efficiency (IWUE) of between 7.1–34.5 % as compared to the non-aerated treatment. Using 19 studies, a meta-analysis was conducted by Du et al. (2018) and they reported a c. 18 % enhancement of WUE through aeration that included all types of gas filling as mentioned in our review. In response to oxygation (a term used to denote aerated drip irrigation), Bhattarai et al. (2008) showed that soybean and pumpkin had higher season-long water use efficiency, which is a term similar to gross production water use index (GPWUI), and that pumpkin had a considerably higher season-long water use efficiency with oxygation at the deeper of the two emitter depths tested (15 cm vs. 5 cm), suggesting that oxygation alleviated a sustained hypoxia at depth. Many other studies have also confirmed the role of gas filling in boosting crop yield while also increasing WUE (Bhattarai et al., 2006; Chen et al., 2011; Abuarab et al., 2013; Li et al., 2016; Liu et al., 2019; Wang et al., 2021a).

2.4. Effects of water and air flow within ADI on bubble distribution and dissolved oxygen

In agricultural settings, implementing ADI technology requires selecting suitable gas infusion equipment to ensure stable and efficient water and gas transmission within the irrigation network. Optimal management practices ensure the efficiency and uniformity of delivery of water and gas along the irrigation infrastructure.

But uniformity of gas and water delivery is not always guaranteed. Goorahoo et al. (2002), working with venturi ADI, showed an inverse linear relationship between crop yield and the length of drip irrigation tapes due to an uneven distribution of water and gas throughout the network. Indeed, large bubbles tend to exit emitters close to the aeration source, with concomitant but minor reductions in water delivery, and emitters distant from the aeration source receive much less air in bubbles and dissolved oxygen. This generation of unequal bubble sizes can lead to unstable movement within the pipe network and tendencies for bubble fusion, rupture, and premature escape. This results in the aforementioned decline in bubble delivery along the irrigation tape, causing uneven distribution and impacting the uniformity of water flow in the drip irrigation system, thereby limiting effective water and gas transmission (Bhattarai et al., 2015). Indeed, as outlined in Section 2.1.2.5 basic physical principles suggest that tiny bubbles produced by a venturi prolong the air-liquid interface period, slow the rising of bubbles, and extend the period that gases diffuse and remain in solution. After researching various variables influencing the uniformity of venturi ADI systems, Torabi et al. (2013, 2014) concluded that one of the main causes of the decline in uniformity of water and gas delivery to emitters is the highly uneven spatial distribution of macro bubbles in the drip irrigation tape.

Indeed, the transmission process in drip irrigation involves more than just water and gas moving independently; it is a complex interaction between the two, involving momentum and energy exchange. Unlike traditional drip irrigation, where water flows alone, ADI involves a more intricate two-phase flow of gas and liquid. Indeed, even a three-phase flow simulation including gas, liquid and particles has been studied, when considering the relationship between ADI and emitter clogging (Wang et al., 2024c). Understanding how the flow structure of water and gas changes and evolves within the system is crucial when understanding this two-phase flow and its practical importance in aerated drip irrigation systems.

Due to the rapid advancement of modern measurement, imaging, and fluid dynamics computer tools, the study of air-liquid phase flow has proven useful through observation and numerical simulation. Scholars have approached this through theoretical studies, applying conservation principles of mass, momentum, and energy, using fundamental equations of two-phase flow. Su and Midmore (2005) investigated the movement of ADI under steady-state conditions and concluded that water and gas are asymmetrically distributed under the influence of gravity. They also established the dispersion equation for two-phase gas and liquid flow based on two-phase hydrodynamics theory. Using an incompressible two-fluid model as a foundation, Panicker et al. (2018) observed gas-liquid flow instabilities by increasing the dispersion source term, i.e., that related to drag coefficient and the gradient of the gas volume fraction,.

Using image processing techniques, Shanthi and Pappa (2017) identified features related to two-phase flow and proposed a method using fuzzy logic and support vector machine with principal component analysis for two-phase flow recognition of flow patterns for industries with two phase flows, such as in aerated irrigation. In a similar manner, Bhattarai et al. (2013, 2015) used visual testing and image processing to observe the bubble distribution along a venturi aerated drip irrigation tape following different tape orientations and the addition of surfactant. Their data show that these technical parameters had significant impact on bubble distribution and movement and some are discussed shortly. Yin et al. (2015) and Gordiychuk et al. (2016) used high-speed photography with venturi microbubble generation to investigate the characteristics of venturi aeration and to evaluate the development and size distribution of bubbles in the two-phase flow of water and gas. The micro-bubbles generated by the venturi type bubble generator in the study by Gordiychuk et al. (2016) had a mean diameter of 175 μm, somewhat larger than the idealized diameter of < 20 μm as suggested by Bhattarai et al. (2013). Through visualization experiments, Kong et al. (2018) investigated the flow characteristics of gas and liquid and discovered as the large bubbles expanded along the flow direction due to small bubble coalescence, they accelerate resulting in a decrease in void fraction (i.e., the fraction of the channel cross-sectional area occupied by the gas phase).

To improve the uniformity of water and gas transmission in drip irrigation systems and extend their reach, scholars evaluated factors such as the layout of the network, inclusion and concentration of surfactants, types and nominal flow rates of emitters and imposition of 'plugs' close to emitters and some of the outcomes are summarized below.

Large bubbles in the irrigation flow more readily emerge from emitters close to the air source with upward- than downward-facing emitters (Bhattarai et al., 2015), resulting in uneven distribution of water and gas in the drip irrigation tape. They reported that the presence of small bubbles in the drip irrigation tape is beneficial for ensuring the proper distribution of water and gas, leading to a consistent flow of both. As outlined in the digression on bubble size, small bubbles exhibit superior stability and efficiency in mass transfer of oxygen to surrounding water compared to larger bubbles (Li et al., 2014) and are better suited for extending the efficient transportation range, and promotion of even distribution, of water and gas within the pipe network. Hence, in order to enhance the stability of bubbles and maintain the number of small bubbles in the pipe network, researchers introduced low concentrations of surfactants into the water. These enhance the viscosity and elasticity of the bubbles and prevent the fusion between bubbles (Torabi et al., 2014; Lei et al., 2016, 2018), thereby markedly improving the uniformity of delivery of air bubbles along the irrigation tape.

Using a 4 ppm surfactant [BS1000™ (alcohol alkoxylate from Crop Care Australia Pvt. Ltd)], Lei et al. (2020) evaluated the uniformity of water and gas outflow and dissolved oxygen concentration in an aerated drip irrigation system with a Seair Venturi Diffusion System Model

SA75. Indeed, use of the surfactant led to three-fold increases of dissolved oxygen saturation with air injection (50 % in the control and 165 % with surfactant) compared to a non-aerated control along 200 m of non-pressure compensated irrigation tape, and up to 438 % with injection of oxygen, all due to positive effects of MB creation and of increased contact between bubbles and water.

Turbulence-inducing sealing plugs that would penetrate to different depths of the water and air bubbles in the irrigation stream in the pipe during venturi aeration and would create improved bubble distribution along an irrigation tape were tested by Torabi et al. (2014). These plugs dispersed air bubbles away from drip connectors near to the venturi, raised the Christiansen uniformity coefficient of the emitter air flow rates, and increased availability of air bubbles to more distant emitters, thereby increasing the uniformity of air delivery to emitters. When used with surfactant, uniformity was further increased.

Understanding the lifespan of bubbles before dissolution is necessary for the effective implementation of ADI. First lifespan estimations for gas bubbles dissolved in liquids were reported and modelled by Epstein and Plesset (1950) who related them to the concentration of dissolved gas and the surface tension of the gas bubble-water interface. We have argued, as does Navisa et al. (2014), that smaller bubbles have greater efficiency of oxygen transfer than do larger bubbles due to their larger surface area to volume ratios and greater buoyancy and lifespan. Extending this argument to MNB has been theoretically attempted (Fan et al., 2023), but with limitations for NB due to the lack of available empirical data and partly related to the bursting of NB and generation of free radicals.

Based on conventional thermodynamic theory, the potential existence and the stability of NBs has been a contentious issue for a long time (Wu et al., 2012). According to the Young-Place equation, the internal pressure of NBs would be significantly greater than the outward pressure of a solution, causing disappearance of bubbles within microseconds (Snell et al., 2016). Despite this, a number of studies showed that NBs could retain measurable life span lasting hours, days, weeks, or even months (Hu and Xia, 2018), an observation supported by the theoretical studies of Tan et al., (2020). As for use of surfactants in venturi generated bubbles, surfactants extend the stagnation time for NB too (Li et al., 2014). However, in practice, most research on oxygen transfer efficiencies and life span of NBs has focussed on their use in amelioration of contaminated waters; there is still much to research for their use in ADI.

Comparisons of uniformity of supply of air, and consequently of oxygen concentration between various gas filling practices are rare. One such was between micro-bubbles produced by a venturi or a fluidic oscillator, the latter incorporating a micro-porous diffuser that allowed for control of the bubble sizes to approximately 20 µm or less. In this comparison, the fluidic oscillator aeration, with smaller uniform bubble size, maintained a longer duration of elevated dissolved oxygen in the irrigation water by a factor of two compared to the venturi aeration (Lei et al., 2016).

2.5. Other factors affecting the efficacy of ADI for crop growth

2.5.1. Soil texture and water quality constraints

Micro- nano-bubbles effectively work in poorly aerated and fine-textured soils (Baram et al., 2022), especially when deployed with amendments to the soil such as biochar, which offers an oxidation-porous synergistic effect necessary to increase aeration porosity (Ouyang et al., 2025). Nevertheless, there is some evidence indicating that the impact of air nanobubble-saturated water properties on soil moisture and nutrient retention could prove to be lesser when the soil was a heavy clay rather than loamy or sandy soils (Ramiro et al., 2024), or with compost addition (Povilaitis and Arablousabet, 2025). although as presented later, MNBs allow the use of treated wastewater in a sustainable manner controlling biofouling in irrigation systems (Baram et al., 2022). There is however a threat of soil salinization in the event of chemical oxygenation (for example with sodium percarbonate), highlighting the importance of identifying and using methods of MNB generations that will not negatively impact the environment (Wang et al., 2023c).

2.5.2. Operational parameters and dose-dependent effects

The most important parameters for ADI are the characteristics of bubbles. Micro- nano-bubbles are more effective in gaseous transfer than the traditional micro-bubbles from venturi because of their stability, high internal pressure, as well as low buoyancy (Liu et al., 2019), which avoids poor uniformity of bubble delivery along the irrigation tape. Overall, most importantly, there are dose-dependent limits to the benefits. A specific concentration of dissolved oxygen (DO) should be identified to achieve maximum performance in terms of yield and WUE of a crop. For example, 7 mg L^{-1} was recommended over 24 mg L^{-1} for tomato (del Moral torres,et al., 2024), a DO of 9 mg L^{-1} was recommended for cucumber (Ouyang et al., 2023) subsequently raised to 14–15 mg L^{-1} (Ouyang et al., 2025) and raised to 20 mg L^{-1} by Jin et al. (2023). A value of 18 mg L^{-1} was recommended by Ma et al. (2025) for processing tomato and Zhou et al. (2019) also recommended the slightly lower 15 mg L^{-1} for tomato and cucumber. Values of soil oxygen ranged from 17 to 20 mg L^{-1} in studies on tomato and cucumber by Liu et al. (2019), with the slightly higher value better for cucumber. Maize responded better to 30 mg L^{-1} than a lower concentration, so the range of recommendations is somewhere between 9 and 30 mg L^{-1}. A rather strange value of 220 mg L^{-1} total oxygen concentration has also been reported as optimal for tomato (Zhou et al., 2022). A higher level than the optimal may decrease effectiveness. As an example, O_2-NBs increase the production of ROS and thus soil redox capacity, and if the concentration is supra-optimal in the soil solution it may cause oxidative stress in plants (Arablousabet and Povilaitis, 2024).

2.5.3. Uncertainty and Mechanistic Understanding

Many studies fail to adequately report crucial bubble characteristics (size and concentration – Azevedo et al., 2019) even though newer potential methods are more precise in their characterization of bubbles (NTA is performing Nanoparticle Tracking Analysis, Wang et al., 2024d). Also, our understanding of microbially-mediated pathways in response to ADI (16S rRNA gene sequencing/Structural Equation Modeling, Zhou et al., 2022; Chen et al., 2023) is advancing but several gaps remain. In addition, more information is needed on the long-term stabilization of MNB under various types of soil (Arablousabet and Povilaitis, 2024) and how different physiological processes respond to soil oxygen concentrations and result in crop-specific effects, especially where adverse effects of ADI are found, as in species with a low antioxidant capacity (Wang et al., 2020). Continued research focusing on identifying these specific biochemical and microbial thresholds is essential to maximize the efficacy and guarantee the long-term viability and scalability of MNB technology in diverse agricultural settings (Marcelino et al., 2023; Arablousabet and Povilaitis, 2024).

2.6. Effect of gas filling on blockage characteristics of drip irrigation system

As global water scarcity intensifies and industrialization accelerates, polluted water sources present an unending predicament. In agriculture, a critical sector heavily reliant on diverse water sources for irrigation, the situation is particularly dire. Farmers often use heavily laden water sources containing prominent levels of sediment, pollutants, and microorganisms. This presence of "dirty water" greatly heightens the risk of clogging in drip irrigation systems, which are otherwise recognized for their uniformity. Even with “clean” water clogging is evident (Thomas et al., 2025). Numerous studies have indicated that clogged drip irrigation systems experience decreased efficiency, shorter lifespan, and limited applicability (Pei et al., 2014; Han et al., 2019; Li et al., 2020). To improve drip irrigation system efficiency, clogging in emitters must be addressed.

Multifactorial physical, chemical, and/or biological features frequently combine to cause emitter clogging in irrigated agriculture (Feng et al., 2019; Ravina et al., 1992). The interaction of these variables is frequently seen in blockage processes that affect the accumulation of blocking material in irrigation systems (Ravina et al., 1992, 1997; Puig-Bargués et al., 2005; Pei et al., 2014).

An important factor responsible for irrigation equipment blockages is microbial activity. This is primarily because, during microbial metabolism, Extracellular Polymeric Substances (EPS) are produced. These substances have adhesive properties and easily attach to the irrigation channels (Zhou et al., 2014). Since the late 20th century studies have focused on how microbial activity affects drip irrigation systems. In 1980, Picologlou et al. (1980) discovered that microbial community activity leads to the formation of a microbial slime layer on the surface of water pipelines, impacting system performance. Ravina et al. (1992, 1997) further investigated drip irrigation and found that biotic irrigation blockages primarily consisted of gel aggregates containing fine particle organic matter, inorganic substances, and biomass resulting from microbial metabolism. Taylor et al. (1995) reported that biofilms produced by microorganisms play an important role in facilitating the deposition of organic matter, thereby further contributing to blockage of irrigation devices. Biofilms serve as both the initial condition and a triggering factor for emitter clogging, as evidenced by previous research (Tarchitzky et al., 2013). Over time, EPS continuously absorb impurities, including suspended particles from the irrigation water, resulting in the build-up of biofilms that contribute to irrigation device blockages (Li et al., 2013; Zhou et al., 2014). As the chemicals in the irrigation water constantly precipitate on the irrigation walls and biofilm surfaces, the irrigation channel surface roughness changes significantly (Shi et al., 2022), further encouraging the attachment of suspended particles, chemical precipitates and microorganisms. Consequently, using practical methods to control microbial growth can effectively slow down the process of blockage in irrigation devices.

Due to its potent antimicrobial properties, chlorine exhibits strong efficacy in inhibiting microbial growth and preventing the formation of biofilms in irrigation tapes. Consequently, chlorination treatment of drip irrigation systems proves effective in delaying or preventing biological and chemical blockages in irrigation devices. Chlorination is frequently employed as an anti-blockage measure in drip irrigation systems (Puig-Bargués et al., 2005). However, such high frequency or concentration of chlorination will inhibit the root development of crops, reduce the ability of plants to absorb nitrogen and other nutrients, and have a negative impact on crop growth and development (Thomas, 2021). This is where the use of hydrogen peroxide comes to the fore, given its oxygen release property for enhanced root growth, and its •OH hydroxyl oxidizing property which has been shown to reduce dis-uniformity between emitters caused by biofouling (Thomas et al., 2025). With irrigation water in field trials with crops (Thomas et al., 2025), stabilized H_2O_2 at 10 ppm reduced complete emitter clogging by 50 % (from c. 14 % in the control to c. 6 % in the treated plots) and biofoul of emitters by over five times, and yield increases of between 12 % and 49 % were evident for grape, chili and sugarcane. The low concentration of H_2O_2 also reduced root intrusions where manifest compared to the control treatment. Additionally, the stabilizer used (1-hydroxyethylididene-1, 1-diphosphonic acid- HEDP), is known to combat per se calcium scale precipitates in water treatment systems (Thomas et al., 2025). Studies by Japhet et al. (2022) using low concentrations of H_2O_2 (1–2 mg L^{-1} at the emitter outlet for 10 min at the end of each irrigation cycle) in secondarily treated wastewater also prevented emitter clogging and was much more effective than periodical application of concentrated H_2O_2 (i.e., 25 mg L^{-1} weekly in the last 5 min with lateral flushing).

Aeration *per se* also has positive effects on the integrity of emitters. A recent study conducted by Wang et al. (2024c) showed that aeration, using a Mazzei A-20 Venturi tube (with the maximum gas particle size being 15 μm) significantly reduced sand deposition in emitters at various discharge rates. Chemical blockage is also reduced by aeration of irrigation water, as shown by Benlouali et al. (2021) who aerated tertiary treated wastewater to raise its oxygen concentration and reduce its biological and chemical clogging potential prior to its use in golf course irrigation.

In aerated drip irrigation systems, the water and gas environment within the pipe network undergo notable changes, particularly in MNB aerated drip irrigation systems. Micro-nano bubbles play a crucial role in this context by effectively removing suspended organic particles from water, reducing surface chemical deposition, and inhibiting microbial growth (Zhang et al., 2020; Li et al., 2024). Xiao et al. (2020) showed that NBs in irrigation streams decrease deposition of mineral precipitates, reduce microbial-fixed biomass, shift the diversities of bacterial communities in biofilms and inhibit mutualistic microbial interactions, all favorable as mitigation practices for biofouling. Similarly, studied under controlled experimental conditions with the input of fertilization, a 29 % extension of service life of emitters and improvements in uniformity of a drip irrigation system, were related to the beneficial influence of MNB aeration on micromorphological structure and microbial diversity within emitters (Li et al., 2025a). They also reported that MNBs do more than just improve particle dislodgement through the influence of velocity and bubble dynamics, they also promote the chemical and biological degradation of the fouling and biofilm by reactive oxygen species, lessening of the surface tension, and changing the microbial adhesion. Still, one study (Lv et al., 2023) reported an increased risk of particulate blockage when irrigating with muddy water with venturi aeration, especially with smaller particle size, to some extent overcome by placing emitters in an upward facing position. Another study by Li et al., (2023) with an alkaline ground water also showed that both particulate and chemical emitter blockage were aggravated with MNB aeration, greater turbulence with MNB caused collision of particles and their deposition in emitters, with the authors calling for frequent flushing of the irrigation system. Nevertheless, it is most likely that oxidative free •OH produced during bubble collapse of nano-bubbles reduces fixed-biomass and restrains mutualistic interactions among microbial species (Li et al., 2020). Extracellular polymers and biofilm biomass were decreased, resulting in an extension of emitter service life by 130 %. Indeed, it is reported that NBs produce localized high temperatures, high pressures, and hydroxyl radicals with strong oxidative activity that kill microorganisms in the collapsing process of NB (Atkinson et al., 2019). This induces degradation of organic matter (Sung et al., 2017), thereby slowing down protein adsorption on surfaces (Liu and Craig, 2009), consequently diminishing biofouling in agricultural water distribution systems (Li et al., 2020).

Experiences differ in terms of MNB ADI ability to mitigate emitter clogging, hence to more fully realize the potential of MNB coupled ADI systems further studies are needed in different soil, water and environmental conditions. This need becomes more acute as the use of treated wastewater becomes more common in irrigated agriculture requiring greater focus on the relationship between microbial community activities and emitter blockage.

2.7. *Comparative economic and technical analysis of aeration technologies*

Beyond technical performance, the economic feasibility of aeration technologies is pivotal for their practical adoption in drip irrigation systems. The overall cost–benefit ratio is defined by equipment investment, operating expenses (energy, maintenance, and chemical inputs), oxygen transfer efficiency, and crop yield response. Given the reported yield benefits over no aeration, a simple cost: benefit analysis with a retro-fitted venturi-aerated cotton on a total of 5.2 ha (Pendergast et al., 2013) showed that a payback period of *c.* 4 years would cover the c. A $1200 ha^{-1} installation cost, with the system running successfully for 9 years and expected to be serviceable for 20 years.

Micro-nano bubble systems offer similar agronomic and economic benefits by being able to optimize crop quality and quantity, as well as minimizing the input requirements through synergistic mechanisms. Besides yield benefits, studies have established that MNB aeration can lower the application of chemical fertilizers and emissions of methane by 20 percent (in paddy rice), and improve irrigation efficiency, with concomitant economic benefits (Chirwa et al., 2024). These benefits come at some cost; yet they result in higher overall economic benefits than conventional drip irrigation alone (He et al., 2022). The capital cost of MNB generators is the most expensive of all aeration techniques; there are commercially sold nanobubble apparatuses that usually cost more than 10,000 yuan (*c*. US$1400, Wang et al., 2023c). Another generator unit was cited as costing about US$1317.5 (with a 10-year depreciation assumed – He et al., 2022), while a mobile unit used for half a hectare experiments cost approximately 1720 USD (Liu et al., 2019). However, with the exception of Liu et al. (2019), the crop area that each unit could service, and their operative lifespan, have not been reported to our knowledge. Comparatively, venturi air injectors, are more popular in field irrigation because they are operational simple to use and have low associated costs (Wang et al., 2024c). Despite the low-cost alternative of venturis, MNB generators may justify their higher price through superior efficiency in dissolved oxygen transfer and sustained presence in water, which ultimately drives the synergistic benefits of reduced resource consumption and increased yields (Park et al., 2010; Junejo et al., 2025). However, a single year field comparison between a venturi and an MNB generator, with irrigated processing tomatoes, showed that although the value of the harvested crop was greater with the MNB generator, the net profit was significantly greater for the venturi due to the lower cost of the latter (Wang et al., 2025b). Nevertheless, others (e.g., Zhu et al., 2021) suggest that MNB generators combine benefits of low energy consumption and simplicity for management and are environmentally friendly.

Simple air injection systems which are based on the use of a compressor or blower have the benefit of being less complex and less expensive than venturi or MNB generators. However, their main expense is that of the compression energy (Ben-Noah and Friedman, 2018). The estimated annual price of a model of blower in a direct air injection system used for a 1.5 ha area was estimated to be US$200 ha^{-1} per year for the equipment, assuming a 10-year lifespan, and annually $2200 ha^{-1} for electricity and maintenance to operate (Ben-Noah et al., 2021). An 8.7% yield increase of oranges with the compressed air system would breakeven for growers, a yield increase easily achievable with air injection under oxygen stress in the field in Israel.

Economic analyses pertaining to chemical gas filling are even rarer than those for mechanical gas filling. One study (Bhattarai et al., 2004) reported a cost per hectare of A$63 for four weekly applications of hydrogen peroxide leading to a 4 t ha^{-1} yield increase of zucchini, but another study on various crops in large scale plots also using hydrogen peroxide did not include economic analyses (Thomas et al., 2025), although the authors wrote given 'the magnitude of the yield benefits, they are likely to be favourable'.

3. Ongoing issues with, and opportunities for, aerated drip irrigation

To date, substantial research has been conducted on the benefits of aerated irrigation particularly for the enhancement of the hypoxic soil environment, crop growth, and resultant yield and quality, water and fertilizer use efficiencies, and drip irrigation system uniformity. Researchers have made significant scientific advances, laying the groundwork for further development of ADI. This research has been disparate in terms of comparisons of effects of different ADI practices, soil and crop types, water sources and the general cropping environment. In ADI development, key challenges persist. These include firstly addressing rapid gas dissolution and inconsistency of bubble size, the latter which greatly affects stability in solution, for it is quite clear that bubble size [macro, micro and nano] plays a significant role in the mixing and transmission of water and gas in drip irrigation systems. Secondly the interaction between ADI and other water saving practices needs research attention, with consideration to the effects of excessive/uneven aeration on root morphology and soil microbial community. Thirdly studies on emitter blockage must be expanded, and fourthly the identification of the gamut of optimal ADI practices, according to local conditions needs clarification. This should be followed by attention to scaling up practices. Yet in spite of these foci for research and development, opportunities arise for widespread use of ADI in addressing soil remediation, enhancement of sewage water as an irrigation input, and improvement of nutrient and other resource use efficiency, in addition to its use as a source of oxygen in oxygen-deficient soils. These are detailed as follows.

3.1. Issues requiring further research and development to enhance adoption of ADI

3.1.1. Gas production and movement characteristics of water and gas in the drip irrigation tape

Research on the uniformity of gas-filling drip irrigation systems primarily focuses on achieving even distribution of water and gas, and on the factors that influence this. However, there is insufficient attention given to the spatial distribution and uniformity of water, soluble fertilizer (as in fertigation), and gas with different filling methods, and the impact of relevant technical parameters such as emitter flow rate, working pressure, and drip orientation (facing up or down) on this distribution. Also, bubbles with varying physico-chemical characteristics and differential flow rates caused by valve operation significantly affect efficacy of ADI, and these need further research attention. Given the context of modern agricultural water conservation and the adoption of new water-saving technologies, it is imperative to comprehensively examine the influence of various technical parameters on the spatial distribution uniformity of water, fertilizer, and gas in ADI systems.

Venturi injectors and MNB generators are the most commonly used mechanical gas filling devices in ADI as illustrated with references cited to date. However, these devices produce bubbles with differing gas production effects, due to variations in their bubble size and oxidation properties, which directly impact the movement of water and gas within the drip irrigation system, and their behavior upon exit from emitters. A major constraint in DI and SDI using a venturi for air injection is that, as noted earlier, most of the bubbles coalesce and exit the drip tape within a short distance from the air injector (Bhattarai et al., 2013; Goorahoo et al., 2002). With venturi injectors, much of the air void fraction is in large bubbles, with a relatively small fraction in micro-bubbles (Bhattarai et al., 2013). Although scholars have investigated the distribution of air bubbles in distinct locations within the drip irrigation tapes in studies on venturi aerated drip irrigation (Torabi et al., 2013, 2014; Torabi and Miranzadeh, 2021), limited published research has focused on (a) the import and export pressure difference of a venturi and associated pump capacity, (b) the optimal liquid flow rate (Wang et al., 2023d), and (c) internal flow characteristics that directly influence bubble production and aeration efficiency (Baylar and Ozkan, 2006; Dange and Warkhedkar, 2023), all crucial factors affecting venturi performance. Likewise, alterations of fluidic oscillator pressure differential can alter the spectrum of hydrodynamic caviation (Liu et al., 2022).

With venturi generation of MBs, the magnitude of the venturi pressure difference directly affects the cavitation intensity, which in turn regulates the size distribution of micro- and NBs, the latter for example as produced by a bubble generator based on venturi-type recirculating hydrodynamic cavitation (Li et al., 2021). A larger pressure difference leads to a more intense cavitation collapse process, producing smaller-sized bubbles. The higher the pressure difference, the higher the cavitation intensity at the throat and the higher the bubble generation efficiency and concentration (Hasani Malekshah et al., 2022). In addition, cavitation collapse induced by differential pressure can accelerate bubble fragmentation through micro-jets, further reducing the bubble size (Wang et al., 2024a). However, at the same time that increasing pressure can increase DO, it can also cause substantial coalescence and/or entrapment effects between NBs and MBs, leading to a decrease in NB concentration (Li et al., 2021). According to Henry's law, the change of differential pressure regulates the dissolution and release of gases in liquids. Differential pressure drives the dissolution of gases before releasing them through pressure recovery, forming stable micro- and nano-bubbles. In a venturi-vortex MB generator (De Oro Ochoa et al., 2022), the inlet and outlet pressure differentials together with the gas/liquid flow ratio affect bubble generation. Lower flow ratios (i.e., higher gas flow rates) require greater differential pressure to drive gas injection, resulting in higher concentrations of MBs. In addition, the differential pressure regulates the mixing efficiency of the gas and liquid, affecting the homogeneity and stability of the bubbles (De Oro Ochoa et al., 2022). For MNB aerated drip irrigation, further research is needed particularly on the gas production characteristics of MNB generators, and on the study of gas and liquid mixed flow within the drip irrigation root zone (Liu et al., 2019; Zhou et al., 2022). Such experimental observations require further research attention to assist in the efficient adaptation and generation of MNB and the efficiencies of gas production, and the water and gas transmission processes, for MNB use in drip and possibly in the future flood, irrigation.

Therefore, it is imperative to delve deeper into the efficiencies, to determine the adaptation conditions for different gas filling methods.

3.1.2. Gas filling used with other practices for saving water

It will be important to determine the impact of ADI when superimposed on the practices of partial root zone drying and deficit irrigation, both well-known for their high water use efficiencies. One study with tomato (Zhu et al., 2020) comparing the effect of with or without Mazzei venturi SDI showed the benefit of aeration to be less the greater the irrigation deficit, in line with the thesis that aeration obviates soil oxygen deficiency caused by saturated wetting fronts near the drippers. Nevertheless, in contrast a recent study (Calvo et al., 2025) with turfgrass showed that the benefit of NBs, quantified as measures of normalized difference vegetation indices and red, green, blue vegetation indices was greater under high water restrictions (a 50 % restriction in irrigation volume compared to a 30 % or no restriction). The latter effect was linked by the authors to the ability of NB to generate reactive oxygen species, leading through improved physiological processes to a more efficient use of limited water. In addition, even with high water restriction, saturated wetting fronts may occur around emitters, but for shorter duration compared to those with full irrigation. Combinations of ADI with imposition of raised beds, and with biochar applications, complementary practices known to improve WUE (Tang et al., 2024; Oo et al., 2018), are also in need of further research.

3.1.3. Influence of gas filling on the blockage characteristics (emitter clogging) in drip irrigation tapes

The blockage issue in irrigation significantly hampers the performance, service life, and adoption of drip irrigation systems. Emitter clogging is a multifaceted process managed to a degree by varying aeration methods, which differentially affect biological, physical, and chemical clogging mechanisms. Current research remains insufficient to systematically elucidate the impact of aerated irrigation on clogging dynamics. Monitoring the dynamic process of irrigation blockage and investigating the mechanisms of blockage in ADI systems as a start will aid in clarifying the impact of gas filling on drip irrigation system performance (Lv et al., 2023). Future investigations should focus on: (a) transport and reaction mechanisms between bubbles and clogging substances, particularly the interplay of physical properties, chemical characteristics, and biological interactions, (b) microscopic mechanisms underlying clogging evolution under aerated conditions, including biofilm detachment patterns and particle aggregation behaviors influenced by MNBs, (c) development of ecofriendly and efficient anti-clogging technologies, such as optimizing emitter geometry and integrating advanced aeration control systems, (d) establishment, by investigating the fundamental mechanism of ADI influence on emitter clogging. of robust anti-clogging frameworks and a comprehensive model of ADI that balances the uniformity of water and fertilizer application in drip irrigation systems and the service life of the same, so as to ensure the reliability of ADI systems.

These advancements will facilitate the design of safe, efficient, and sustainable aerated drip irrigation systems, ultimately enhancing water-use efficiency and crop productivity.

3.1.4. Cross environment studies on impact of ADI

As our review has shown, ADI in its various facets, has in the main been successful across a range of soil types, crops and weather conditions in improving yields. But definitive recommendations as to the choice of which aeration device and bubble distribution suits which soil and crop types, and prevailing economic conditions, are lacking. We propose the setting up of a coordinated network, using specified side-by-side standardized ADI treatments with common crops and water sources and other agronomic conditions at the field scale. Superimposed in a factorial design, such experiments will enable separation of all main effects and interaction, such that recommendations as to adoption of ADI will be superior to those based on the current piece-meal experiments. Such trials are required to fully assess the potential of ADI and to provide practical recommendations for its global application, and to underpin efforts for scaling up. Close interaction with developers and suppliers of irrigation technology is called for in these proposed studies and with scaling up.

3.1.5. Scaling up

Although there is an increasing interest in adopting ADI, existing studies are limited with the majority being performed under small-scale field or greenhouse conditions. The efficiency, scalability and economic viability of various ADI technologies in the field is significantly under-researched.

One significant obstacle to farmer adoption and scaling up is most likely the question about economic viability. Policy intervention to assist with costs such as acquisition of the aeration device, and with electricity and maintenance costs are paramount. Similarly, other potential bottlenecks, where policy and subsidy interventions are necessary, include education for practical implementation, for example assisting with skilling up of operators and aerator maintenance, and scaling between small plots and large-scale farm. Further investigations should be directed towards cost benefit analyses, and life cycle assessments of aerators under various environments to determine the viability of using ADI in practice among farmers in different locations, in parallel with scaling up efforts.

3.2. Opportunities afforded by ADI

3.2.1. Amelioration of contaminated soils, including heavy metals, organic pollutants, antibiotics, and the like

Future MNB aeration irrigation technologies applied to irrigation will not only increase crop yield and quality, but also address organic pollutants and heavy metals, ground-water bioremediation, and enhance the possibility of sewage resource utilization (Li et al., 2014; Favvas et al., 2021). For instance, surfactant-containing MNBs were able to effectively eliminate polycyclic aromatic hydrocarbons in the soil and ground water by enhancing soil diffusion and minimizing adsorption (Han et al., 2025) whereas MNB hydrogen water through subsurface drip irrigation boosted plant growth, stress-response phytohormones, and rhizosphere microbial community, which, due to reduced Cd bioavailability, reduced Cd uptake in *Ipomoea aquatica* (Forssk) (Guo et al., 2025). Owing to their unique physicochemical and biological properties, MNBs exhibit significant potential in oxidizing organic pollutants and disinfecting pathogens by generating reactive oxygen species (ROS, including •OH, superoxide anion radicals and singlet oxygen), thereby effectively removing persistent organic pollutants and heavy metals upon NB collapse and inactivating harmful microorganisms (Lyu et al., 2019; Fan et al., 2021a).

Therefore to address risks associated with residual organic contaminants and microbial pathogens in recycled irrigation water, future research should prioritize: (a) investigation of the spatiotemporal migration patterns of nutrients under aerated irrigation with recycled water, (b) elucidation of the degradation pathways of persistent organic pollutants at soil-water interfaces, particularly focusing on enzyme-microbe interactions, (c) deciphering the mechanisms for inactivation pathways, for example of *Escherichia coli*, *Salmonella* and other pathogens through ROS-mediated oxidative stress and biofilm disruption, and (d) developing a "bubble-soil-crop" integrated irrigation framework to optimize water-nutrient-bubble interactions and establishing safety criteria for recycled water irrigation and soil remediation based on contaminant bioavailability, microbial viability thresholds and MNB generation.

3.2.2. *Enhance resource use efficiency with ADI*

To date, research on drip irrigation system performance has primarily focused on the uniform distribution of water and gas using venturi drip irrigation systems, with associated improvements in crop yield and water use efficiency, without delving deeply into drip fertigation. Section 2.3.1 refers to studies where improvements in nutrient usage have been reported. Whether it is as a saving of fertilizer input, such as reported by He et al. (2022) with NB irrigation, and attributed to increasing expression of genes responsible for development and growth (Wang et al., 2021b), or the delivery of oxygen to anoxic root zones that enables nutrient uptake (as illustrated by Bhattarai et al., 2010), ADI has much to offer in terms of enhanced nutrient use efficiency and reducing negative environmental impact. Nano technology in terms of nutrient formulation is gaining ground (Ahmed and Mohamed, 2025) and should be trialled in combination with ADI to see if synergies in improved crop performance may be gained. Likewise, combination of ADI with nano-biopesticides (Vinci et al., 2025) deserves attention.

Indeed, the term 'multigation' has been introduced by Bhattarai et al. (2010) to encompass the objective delivery of all soil-based inputs in a coordinated manner. ADI is an integral part of this and further studies on the expanded opportunities for improvements with ADI in resource use efficiency, particularly of nutrient and pesticide delivery, are called for.

Such advances taken together will provide theoretical foundations and technical paradigms for sustainable agricultural water and contaminated land reuse, positioning MNB-enhanced drip irrigation as a pivotal strategy for circular agriculture and soil health restoration.

4. Conclusions

Currently, the efficient use of water in agriculture falls short of meeting the demands for modern agricultural development. ADI is an innovative application of water-saving yield-enhancing technologies designed to maintain irrigation conditions optimal for crop growth. It provides for the best distribution of water and gas in the crop root zone growth environment, significantly improving the soil oxygen concentration content therein. This can effectively address the issue of oxygen deficiency in the intra-root zone during and after irrigation and improve the soil environment for the survival/multiplication of the microbial community. It also promotes the development of the crop root system and enhances the physiological performance of the crop.

Moreover, OH hydroxyls produced during MNB bubble collapse in ADI system and through use of H_2O_2 and other peroxides significantly address the clogging problem of the drip irrigation system, by oxidation of organic compounds causing emitter blockage and eradicating microorganisms responsible for clogging. This extends infrastructure service life and enhances the uniformity and efficiency of irrigation. Therefore, ADI technology holds high application value and significant research importance when facing challenges and limitations of irrigation technology. Studies on the movement characteristics and distribution of water and gas in the drip irrigation network, the influence of water-fertilizer-gas integration conditions on clogging characteristics, and the remediation of the soil environment and pollutants are called for. Future research must explore these areas to optimize the application of ADI technology and to comprehensively assess its applicability in modern agriculture. This could well be extended to other irrigation practices, e.g., furrow irrigation, using MNB technologies. To fully explore ADI potential in agriculture, further long-term field research assessing the agronomic and economic effectiveness of various ADI systems under various soil, water, and environmental conditions is essential. These results will enhance knowledge of ADI in practical applications, aid in the creation of technical standards, and guide the promotion of policies to promote farmer adoption.

CRediT authorship contribution statement

Hao Li: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Abdul Rahim Junejo:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **David Midmore:** Writing – review & editing, Methodology, Investigation. **Shakeel Ahmed Soomro:** Writing – review & editing.

Funding

This work was supported by the Henan Provincial Science and Technology Research Project (242102110226); the National Natural Science Foundation of China (52009137); the Central Public-interest Scientific Institution Basal Research Fund (No. IFI2024–18); and the Agricultural Science and Technology Innovation Program of the Chinese Academy of Agricultural Sciences.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data were used for the research described in the article.

References

Abuarab, M., Mostafa, E., Ibrahim, M., 2013. Effect of air injection under subsurface drip irrigation on yield and water use efficiency of corn in a sandy clay loam soil. J. Adv. Res. 4, 493–499. https://doi.org/10.1016/j.jare.2012.08.009.
Abu-Hamdeh, N.H., 2003. Effect of compaction and deep tillage on soil hydraulic and aeration properties and wheat yield. Commun. Soil. Sci. Plant. Anal. 34, 2277–2290. https://doi.org/10.1081/CSS-120024063.
Ahmadi, R., Khodadadi Darban, A., 2013. Modeling and optimization of nano-bubble generation process using response surface methodology. Int. J. Nanosci. Nanotechnol. 9, 151–162.
Ahmed, A.R., Mohamed, H.I., 2025. Nanofertilizers: smart solutions for sustainable agriculture and the global water crisis. Planta 262, 26. https://doi.org/10.1007/s00425-025-04737-7.
Ahmed, A.K.A., Shi, X., Hua, L., Manzueta, L., Qing, W., Marhaba, T., Zhang, W., 2018. Influences of air, oxygen, nitrogen, and carbon dioxide nanobubbles on seed germination and plant growth. J. Agric. Food Chem. 66, 5117–5124. https://doi.org/10.1021/acs.jafc.8b00333.
Arablousabet, Y., Povilaitis, A., 2024. The impact of nanobubble gases in enhancing soil moisture, nutrient uptake efficiency and plant growth: a review. Water 16, 3074. https://doi.org/10.3390/w16213074.
Arwadi, O.E., Saman, Z., Waheed, Z., 2023. An overview of nanobubbles generation in fluid: mechanisms and techniques. Preprint 1–9.
Asplund, P.T., Curtis, W.R., 2001. Intrinsic oxygen use kinetics of transformed plant root culture. Biotechnol. Prog. 17, 481–489. https://doi.org/10.1021/bp010038v.
Assouline, S., Narkis, K., 2013. Effect of long-term irrigation with treated wastewater on the root zone environment. Vadose Zone J. 12, 1–10. https://doi.org/10.2136/vzj2012.0216.

Atkinson, A.J., Apul, O.G., Schneider, O., Garcia-Segura, S., Westerhoff, P., 2019. Nanobubble technologies offer opportunities to improve water treatment. Acc. Chem. Res. 52, 1196–1205. https://doi.org/10.1021/acs.accounts.8b00606.
Azevedo, A., Oliveira, H., Rubio, J., 2019. Bulk nanobubbles in the mineral and environmental areas: updating research and applications. Adv. Colloid Interface Sci. 271, 101992. https://doi.org/10.1016/j.cis.2019.101992.
Baram, S., Weinstein, M., Evans, J.F., Berezkin, A., Sade, Y., Ben-Hur, M., 2021. Irrigation with treated wastewater containing nanobubbles to aerate soils and reduce nitrous oxide emissions. J. Clean. P. 280, 124509. https://doi.org/10.1016/j.jclepro.2020.124509.
Baram, S., Weinstein, M., Evans, J.F., Berezkin, A., Sade, Y., Ben-Hur, M., Bernstein, N., Mamane, H., 2022. Drip irrigation with nanobubble oxygenated treated wastewater improves soil aeration. Sci. Hortic. 291, 110550. https://doi.org/10.1016/j.scienta.2021.110550.
Baylar, A., Ozkan, F., 2006. Applications of venturi principle to water aeration systems. Environ. Fluid Mech. 6, 341–357. https://doi.org/10.1007/s10652-005-5664-9.
Benlouali, H., Karmal, I., Cherif Harrouni, M., Ghanbaja, J., Frascari, D., Hamdani, M., Choukr-Allah, R., 2021. Characterization of clogging deposits in an irrigation pipeline and effect of post-aeration on clogging potential of tertiary-treated wastewater. Water Sci. Technol. 83, 309–321. https://doi.org/10.2166/wst.2020.552.
Ben-Noah, I., Friedman, S.P., 2016a. Aeration of clayey soils by injecting air through subsurface drippers: lysimetric and field experiments. Agric. Water Manag. 176, 222–233. https://doi.org/10.1016/j.agwat.2016.06.015.
Ben-Noah, I., Friedman, S.P., 2016b. Oxygation of clayey soils by adding hydrogen peroxide to the irrigation solution: lysimetric experiments. Rhizosphere 2, 51–61. https://doi.org/10.1016/j.rhisph.2016.08.002.
Ben-Noah, I., Friedman, S.P., 2018. Review and evaluation of root respiration and of natural and agricultural processes of soil aeration. Vadose Zone J. 17, 1–47. https://doi.org/10.2136/vzj2017.06.0119.
Ben-Noah, I., Nitsan, I., Cohen, B., Kaplan, G., Friedman, S.P., 2021. Soil aeration using air injection in a citrus orchard with shallow groundwater. Agric. Water Manag. 245, 106664. https://doi.org/10.1016/j.agwat.2020.106664.
Bera, T., Inglett, K.S., Liu, G.D., 2020. Effects of solid oxygen fertilizers and biochars on nitrous oxide production from agricultural soils in Florida. Sci. Rep. 10, 21754. https://doi.org/10.1038/s41598-020-78198-1.
Bhattarai, S.P., Balsys, R.J., Eichler, P., Midmore, D.J., Wassink, D., 2015. Dynamic changes in bubble profile due to surfactant and tape orientation of emitters in drip tape during aerated water irrigation. Int. J. Multiph. Flow. 75, 137–143. https://doi.org/10.1016/j.ijmultiphaseflow.2015.05.008.
Bhattarai, S.P., Balsys, R.J., Wassink, D., Midmore, D.J., Torabi, M., 2013. The total air budget in oxygenated water flowing in a drip tape irrigation pipe. Int. J. Multiph. Flow. 52, 121–130. https://doi.org/10.1016/j.ijmultiphaseflow.2013.01.004.
Bhattarai, S.P., Huber, S., Midmore, D.J., 2004. Aerated subsurface irrigation water gives growth and yield benefits to zucchini, vegetable soybean and cotton in heavy clay soils. Ann. Appl. Biol. 144, 285–298. https://doi.org/10.1111/j.1744-7348.2004.tb00344.x.
Bhattarai, S.P., Midmore, D.J., Pendergast, L., 2008. Yield, water-use efficiencies and root distribution of soybean, chickpea and pumpkin under different subsurface drip irrigation depths and oxygation treatments in vertisols. Irrig. Sci. 26, 439–450. https://doi.org/10.1007/s00271-008-0112-5.
Bhattarai, S.P., Midmore, D.J., Su, N., 2010. Sustainable irrigation to balance supply of soil water, oxygen, nutrients and agro-chemicals. In: Lichtfouse, E. (Ed.), Biodiversity, Biofuels, Agroforestry and Conservation Agriculture. Springer, Dordrecht, pp. 253–286. https://doi.org/10.1007/978-90-481-9513-8_9.
Bhattarai, S.P., Pendergast, L., Midmore, D.J., 2006. Root aeration improves yield and water use efficiency of tomato in heavy clay and saline soils. Sci. Hortic. 108, 278–288. https://doi.org/10.1016/j.scienta.2006.02.011.
Bhattarai, S.P., Su, N., Midmore, D.J., 2005. Oxygation unlocks yield potentials of crops in oxygen-limited soil environments. Adv. Agron. 88, 313–377. https://doi.org/10.1016/S0065-2113(05)88008-3.
Bian, Q., Dong, Z., Zhao, Y., Feng, Y., Fu, Y., Wang, Z., Zhu, J., Ma, L., 2025. Micro-/nanobubble oxygenation irrigation enhances soil phosphorus availability and yield by altering soil bacterial community abundance and core microbial populations. Front. Plant Sci. 15, 1497952. https://doi.org/10.3389/fpls.2024.1497952.
Bonachela, S., Acuña, R.A., Magan, J.J., Marfa, O., 2010. Oxygen enrichment of nutrient solution of substrate-grown vegetable crops under Mediterranean greenhouse conditions: oxygen content dynamics and crop response. Span. J. Agric. Res. 8, 1231–1241. https://doi.org/10.5424/sjar/2010084-1203.
Bryce, J.H., Focht, D.D., Stolzy, L.H., 1982. Soil aeration and plant growth response to urea peroxide fertilization. Soil Sci. 134, 111–116. https://doi.org/10.1097/00010694-198208000-00005.
Brzezinska, M., Stepniewski, W., Stepniewska, Z., Przywara, G., Wlodarczyk, T., 2001. Effect of oxygen deficiency on soil dehydrogenase activity in a pot experiment with triticale cv Jago vegetation. Int. Agrophy. 15, 145–149.
Busscher, W.J., 1982. Improved growing conditions through soil aeration. Commun. Soil Sci. Plant Anal. 13, 401–409. https://doi.org/10.1080/00103628209367278.
Calvo, J.D., Del Campo, T.V., Acuna, A.A., 2025. Irrigation water treated with oxygen nanobubbles decreases irrigation volume while maintaining turfgrass quality in central Chile. Grasses 4, 6. https://doi.org/10.3390/grasses4010006.
Chen, W., Bastida, F., Liu, Y., Zhou, Y., He, J., Song, P., Li, Y., 2023. Nanobubble oxygenated increases crop production via soil structure improvement: the perspective of microbially mediated effects. Agric. Water Manag. 282, 108263. https://doi.org/10.1016/j.agwat.2023.108263.
Chen, X., Dhungel, J., Bhattarai, S.P., Torabi, M., Pendergast, L., Midmore, D.J., 2011. Impact of oxygation on soil respiration, yield and water use efficiency of three crop species. J. Plant Ecol. 4, 236–248. https://doi.org/10.1093/jpe/rtq030.
Chen, H., Hou, H., Wang, X., Zhu, Y., Saddique, Q., Wang, Y., Cai, H., 2018. The effects of aeration and irrigation regimes on soil CO_2 and N_2O emissions in a greenhouse tomato production system. J. Integr. Agric. 17, 449–460. https://doi.org/10.1016/S2095-3119(17)61761-1.
Chen, X., Lyu, D., Wang, Z., Zong, R., Wen, Y., Zou, J., 2021. Effects of water and nitrogen coupling on the yield and quality of processing tomato under aerated irrigation. J. Agric. Sci. Technol. 23, 191–200. ⟨https://www.nkdb.net/EN/10.13304/j.nykjdb.2020.0821⟩.
Chen, H., Shang, Z., Cai, H., Zhu, Y., 2019. Irrigation combined with aeration promoted soil respiration through increasing soil microbes, enzymes, and crop growth in tomato fields. Catalysts 9, 945. https://doi.org/10.3390/catal9110945.
Chirwa, W., Li, P., Zhan, H., Zhang, Y., Liu, Y., 2024. Application of fine bubble technology toward sustainable agriculture and fisheries. J. Clean. Prod. 449, 141629. https://doi.org/10.1016/j.jclepro.2024.141629.
Crawford, R.M.M., Braendle, R., 1996. Oxygen deprivation stress in a changing environment. J. Exp. Bot. 47, 145–159. https://doi.org/10.1093/jxb/47.2.145.
Cui, B.J., Niu, W.Q., Du, Y.D., Zhang, Q., 2020a. Response of yield and nitrogen use efficiency to aerated irrigation and N application rate in greenhouse cucumber. Sci. Hortic. 265, 109220. https://doi.org/10.1016/j.scienta.2020.109220.
Cui, B., Niu, W., Du, Y., Zhang, Q., 2020b. Effects of nitrogen application and aerated irrigation on soil environment and yield in cucumber root area. Water Sav. Irrig. 4, 27–32.
Dange, A., Warkhedkar, R., 2023. An experimental study of venturi aeration system. Mater. Today Proc. 72, 615–621. https://doi.org/10.1016/j.matpr.2022.08.155.
Day, S.D., Bassuk, N.L., Van Es, H., 1995. Effects of four compaction remediation methods for landscape trees on soil aeration, mechanical impedance and tree establishment. J. Environ. Hortic. 13, 64–71. https://doi.org/10.24266/0738-2898-13.2.64.
De Oro Ochoa, E., Carmona García, M., Durango Padilla, N., Martínez Remolina, A., 2022. Design and experimental evaluation of a Venturi and Venturi-Vortex microbubble aeration system. Heliyon 8, e10824. https://doi.org/10.1016/j.heliyon.2022.e10824.
Del Moral Torres, F., Hernández Maqueda, R., Meca Abad, D.E., 2024. Enhancing root distribution, nitrogen, and water use efficiency in greenhouse tomato crops using nanobubbles. Horticulturae 10, 463. https://doi.org/10.3390/horticulturae10050463.
Dhungel, J., Bhattarai, S., Midmore, D., 2012. Aerated water irrigation (oxygation) benefits to pineapple yield, water use efficiency and crop health. Adv. Hort. Sci. 26, 3–16. https://doi.org/10.13128/ahs-12746.
Drew, M.C., Lynch, J.M., 1980. Soil anaerobiosis, microorganisms, and root function. Annu. Rev. Phytopathol. 18, 37–66. https://doi.org/10.1146/annurev.py.18.090180.000345.
Du, Y.-D., Niu, W.-Q., Gu, X.-B., Zhang, Q., Cui, B.-J., Zhao, Y., 2018. Crop yield and water use efficiency under aerated irrigation: a meta-analysis. Agric. Water Manag. 210, 158–164. https://doi.org/10.1016/j.agwat.2018.07.038.
Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., Best, N., Eisner, S., Fekete, B.M., Folberth, C., Foster, I., Gosling, S.M., Haddeland, I., Khabarov, N., Ludwig, F., Masaki, Y., Olin, S., Rosenzweig, C., Ruane, A.C., Satoh, Y., Schmid, E., Stacke, T., Tang, Q., Wisser, D., 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proc. Natl. Acad. Sci. 111, 3239–3244. https://doi.org/10.1073/pnas.1222474110.
Epstein, P.S., Plesset, M.S., 1950. On the stability of gas bubbles in liquid-gas solutions. J. Chem. Phys. 18, 1505–1509. https://doi.org/10.1063/1.1747520.
Essah, S.Y., Holm, D.G., 2020. Air injection of subsurface drip irrigation water improves tuber yield and quality of russet potato. Am. J. Potato Res. 97, 432–438. https://doi.org/10.1007/s12230-020-09792-2.
Fan, W., Cui, J., Li, Q., Huo, Y., Xiao, D., Yang, X., Yu, H., Wang, C., Jarvis, P., Lyu, T., Huo, M., 2021a. Bactericidal efficiency and photochemical mechanisms of micro/nano bubble-enhanced visible light photocatalytic water disinfection. Water Res. 203, 117531. https://doi.org/10.1016/j.watres.2021.117531.
Fan, W., Li, Y., Lyu, T., Yu, J., Chen, Z., Jarvis, P., Huo, Y., Xiao, D., Huo, M., 2023. A modelling approach to explore the optimum bubble size for micro-nanobubble aeration. Water Res. 228, 119360. https://doi.org/10.1016/j.watres.2022.119360.
Fan, X.H., Tan, D.P., Li, L., Yin, Z.C., Wang, T., 2021b. Modeling and solution method of gas-liquid-solid three-phase flow mixing. Acta Phys. Sin. 70, 124501. https://doi.org/10.7498/aps.70.20202126.
Favvas, E.P., Kyzas, G.Z., Efthimiadou, E.K., Mitropoulos, A.C., 2021. Bulk nanobubbles, generation methods and potential applications. Curr. Opin. Colloid Interface Sci. 54, 101455. https://doi.org/10.1016/j.cocis.2021.101455.
Feng, J., Li, Y., Liu, Z., Muhammad, T., Wu, R., 2019. Composite clogging characteristics of emitters in drip irrigation systems. Irrig. Sci. 37, 105–122. https://doi.org/10.1007/s00271-018-0605-9.
Friedman, S.P., Naftaliev, B., 2012. A survey of the aeration status of drip-irrigated orchards. Agric. Water Manag. 115, 132–147. https://doi.org/10.1016/j.agwat.2012.08.015.
Ghosh, A., Choi, M., Yoon, D., Kim, S., Kim, J., Yee, J.J., Park, S., 2023. Stream water quality control and odor reduction through a multistage vortex aerator: a novel in situ remediation technology. Water 15, 1982. https://doi.org/10.3390/w15111982.
Gil, M., P.M., Ferreyra, E., R., Barrera, M., C., Zúñiga, E., C., Gurovich, R., L., 2009. Effect of injecting hydrogen peroxide into heavy clay loam soil on plant water status, net CO_2 assimilation, biomass, and vascular anatomy of avocado trees. Chil. J. Agric. Res. 69. https://doi.org/10.4067/S0718-58392009000100012.

Gliński, J., Stępniewski, W., 2018. Soil Aeration and Its Role for Plants, first ed. CRC Press, Boca Raton. https://doi.org/10.1201/9781351076685.

Gomez, E., Garland, J.L., 2012. Effects of tillage and fertilization on physiological profiles of soil microbial communities. Appl. Soil Ecol. 61, 327–332. https://doi.org/10.1016/j.apsoil.2011.10.008.

Goorahoo, D., Adhikari, D., Zoldoske, D., Mazzei, A., Fanucchi, R., 2007. Application of airjection irrigation to cropping systems in California. International Water Technology and Ozone V Conference, p. 1309. Fresno.

Goorahoo, D., Carstensen, G., Zoldoske, D.F., Norum, E., Mazzei, A., 2002. Using air in sub-surface drip irrigation (SDI) to increase yields in bell peppers. Int. Water Irrig. 22, 39–42.

Gordiychuk, A., Svanera, M., Benini, S., Poesio, P., 2016. Size distribution and sauter mean diameter of micro bubbles for a venturi type bubble generator. Exp. Therm. Fluid Sci. 70, 51–60. https://doi.org/10.1016/j.expthermflusci.2015.08.014.

Guo, X., Chen, R., Li, H., Li, G., Zhao, Q., Wang, D., Wang, J., 2025. Micro-nano bubble hydrogen water irrigation improves the Cd tolerance of *Ipomoea aquatica* forssk.: rhizosphere micro-biotas modulation and oxidative stress alleviation. Environ. Pollut. 376, 126394. https://doi.org/10.1016/j.envpol.2025.126394.

Han, Y., Dai, C., Li, J., Li, Z., Zhang, Y., Hon, L.K., Tang, B., Tong, W., Feng, X., 2025. Reversible surfactant combined with micro-nano bubbles and peroxymonosulfate: a method for cyclic remediation of PAHs contaminated soil and groundwater. Sep. Purif. Technol. 354, 129491. https://doi.org/10.1016/j.seppur.2024.129491.

Han, S., Li, Y., Zhou, B., Liu, Z., Feng, J., Xiao, Y., 2019. An in-situ accelerated experimental testing method for drip irrigation emitter clogging with inferior water. Agric. Water Manag. 212, 136–154. https://doi.org/10.1016/j.agwat.2018.08.024.

Hasani Malekshah, E., Wróblewski, W., Majkut, M., 2022. Dissolved air effects on three-phase hydrodynamic cavitation in large scale Venturi- experimental/numerical analysis. Ultrason. Sonochem. 90, 106199. https://doi.org/10.1016/j.ultsonch.2022.106199.

Hashmat, A.J., Afzal, M., Iqbal, S., Amin, I., Arias, C.A., Brix, H., Zafar, I., Riaz, S., Rehman, R.U., Salamatullah, A.M., Wondmie, G.F., Bourhia, M., 2024. Nutrients, surfactants, and aeration in constructed wetlands affect bacterial persistence and metabolic activity during the remediation of crude oil-contaminated water. Bioresour. Bioprocess 11, 40. https://doi.org/10.1186/s40643-024-00757-5.

He, J., Liu, Y., Wang, T., Chen, W., Liu, B., Zhou, Y., Li, Y., 2022. Effects of nanobubble in subsurface drip irrigation on the yield, quality, irrigation water use efficiency and nitrogen partial productivity of watermelon and muskmelon. Int. Agrophy. 36, 163–171. https://doi.org/10.31545/intagr/150413.

He, Y., Zhang, T., Lv, L., Tang, W., Wang, Y., Zhou, J., Tang, S., 2023. Application of microbubbles in chemistry, wastewater treatment, medicine, cosmetics, and agriculture: a review. Environ. Chem. Lett. 21, 3245–3271. https://doi.org/10.1007/s10311-023-01640-z.

Heuberger, H., Livet, J., Schnitzler, W., 2001. Effect of soil aeration on nitrogen availability and growth of selected vegetables - preliminary results. Acta Hortic. 147–154. https://doi.org/10.17660/ActaHortic.2001.563.18.

Hongna, L., Shaozhong, K., Taisheng, D., Ling, T., Risheng, D., Si'en, L., 2018. Current status and future research trends on water-saving high-efficiency and eco-friendly agriculture. J. Agric. 8, 163–170. https://doi.org/10.11923/j.issn.2095-4050.cjas2018-1-163.

Hou, H., Chen, H., Cai, H., Yang, F., Li, D., Wang, F., 2016. CO_2 and N_2O emissions from Lou soils of greenhouse tomato fields under aerated irrigation. Atmos. Environ. 132, 69–76. https://doi.org/10.1016/j.atmosenv.2016.02.027.

Hou, J., Zhang, D., Zhou, J., Xu, Z., Mou, P., Cao, Y., Zhu, J., 2021. Oxygenated compound fertilizer improved rice yield by empowering soil aeration. Commun. Soil Sci. Plant Anal. 52, 1798–1810. https://doi.org/10.1080/00103624.2021.1900219.

Hu, L., Xia, Z., 2018. Application of ozone micro-nano-bubbles to groundwater remediation. J. Hazard. Mater. 342, 446–453. https://doi.org/10.1016/j.jhazmat.2017.08.030.

Hu, J., Zhu, L., Hu, Z., Zhong, C., Lin, Y., Zhang, J., Jin, Q., 2017. Effects of soil aeration methods on soil nitrogen transformation, rice nitrogen utilization and yield. Trans. Chin. Soc. Agric. Eng. 33, 167–174. https://doi.org/10.11975/j.issn.1002-6819.2017.01.023.

Ityel, E., Ben-Gal, A., Silberbush, M., Lazarovitch, N., 2014. Increased root zone oxygen by a capillary barrier is beneficial to bell pepper irrigated with brackish water in an arid region. Agric. Water Manag. 131, 108–114. https://doi.org/10.1016/j.agwat.2013.09.018.

Jacobsen, C.S., Hjelmsø, M.H., 2014. Agricultural soils, pesticides and microbial diversity. Curr. Opin. Biotechnol. 27, 15–20. https://doi.org/10.1016/j.copbio.2013.09.003.

Janjua, S., Hassan, I., Muhammad, S., Ahmed, S., Ahmed, A., 2021. Water management in Pakistan's Indus basin: challenges and opportunities. Water Policy 23, 1329–1343. https://doi.org/10.2166/wp.2021.068.

Japhet, N., Tarchitzky, J., Chen, Y., 2022. Effectiveness of hydrogen peroxide treatments in preventing biofilm clogging in drip irrigation systems applying treated wastewater. Biofouling 38, 575–592. https://doi.org/10.1080/08927014.2022.2102903.

Jin, C., Lei, H., Chen, J., Xiao, Z., Leghari, S.J., Yuan, T., Pan, H., 2023. Effect of soil aeration and root morphology on yield under aerated irrigation. Agronomy 13, 369. https://doi.org/10.3390/agronomy13020369.

Junejo, A.R., Jinrui, L., Shaikh, I.A., Lakhair, I.A., Hao, L., 2025. Role of micro-nanobubble water aeration on emitter clogging and uniformity of drip irrigation system. Agric. Water Manag. 319, 109820. https://doi.org/10.1016/j.agwat.2025.109820.

Khan, A.R., Nanda, P., Singhandhupe, R.B., Chandra, D., 2002. Effect of irrigation on soil aeration in relation to peanut production. Arch. Agron. Soil Sci. 48, 19–24. https://doi.org/10.1080/03650340212665.

Khan, N., Ray, R.L., Sargani, G.R., Ihtisham, M., Khayyam, M., Ismail, S., 2021. Current progress and future prospects of agriculture technology: gateway to sustainable agriculture. Sustainability 13, 4883. https://doi.org/10.3390/su13094883.

Khan, P., Zhu, W., Huang, F., Gao, W., Khan, N.A., 2020. Micro–nanobubble technology and water-related application. Water Supply 20, 2021–2035. https://doi.org/10.2166/ws.2020.121.

Kong, R., Rau, A., Kim, S., Bajorek, S., Tien, K., Hoxie, C., 2018. Experimental study of horizontal air-water plug-to-slug transition flow in different pipe sizes. Int. J. Heat. Mass Transf. 123, 1005–1020. https://doi.org/10.1016/j.ijheatmasstransfer.2018.03.027.

Lei, H., Bhattarai, S., Balsys, R., Midmore, D.J., Holmes, T., Zimmerman, W., 2016. Temporal and spatial dimension of dissolved oxygen saturation with fluidic oscillator and Mazzei air injector in soil-less irrigation systems. Irrig. Sci. 34, 421–430. https://doi.org/10.1007/s00271-016-0512-x.

Lei, H., Jin, C., Xiao, Z., Chen, J., Leghari, S.J., Pan, H., 2023. Relationship between pepper (*Capsicum annuum* L.) root morphology, inter-root soil bacterial community structure and diversity under water–air intercropping conditions. Planta 257, 98. https://doi.org/10.1007/s00425-023-04134-y.

Lei, H., Liu, H., Balsys, R., Midmore, D.J., Zang, M., Bhattarai, S., 2020. Factors of relevance for improving the uniformity of oxygen distribution in drip irrigation water. Irrig. Drain. 69, 1133–1145. https://doi.org/10.1002/ird.2502.

Lei, H., Liu, H., Bhattarai, S., Balsys, R., Pan, H., 2018. Impacts of gas source and surfactant on gas-water coupling transmission along a long-distance drip tape in one or two line layout under aerated drip irrigation. Trans. Chin. Soc. Agric. Eng. 34, 88–94. https://doi.org/10.11975/j.issn.1002-6819.2018.19.012.

Lei, H., Xia, J., Xiao, Z., Chen, Y., Jin, C., Pan, H., Pang, Z., 2024. Effects of aerated drip irrigation on the soil nitrogen distribution, crop growth, and yield of chili peppers. Plants 13, 642. https://doi.org/10.3390/plants13050642.

Lei, H., Yu, J., Zang, M., Pan, H., Liu, X., Zhang, Z., Du, J., 2022. Effects of water-fertilizer-air-coupling drip irrigation on soil health status: soil aeration, enzyme activities and microbial biomass. Agronomy 12, 2674. https://doi.org/10.3390/agronomy12112674.

Levidow, L., Zaccaria, D., Maia, R., Vivas, E., Todorovic, M., Scardigno, A., 2014. Improving water-efficient irrigation: prospects and difficulties of innovative practices. Agric. Water Manag. 146, 84–94. https://doi.org/10.1016/j.agwat.2014.07.012.

Li, T., Cui, Z., Sun, J., Jiang, C., Li, G., 2021. Generation of bulk nanobubbles by self-developed Venturi-type circulation hydrodynamic cavitation device. Langmuir 37, 12952–12960. https://doi.org/10.1021/acs.langmuir.1c02010.

Li, R., Han, Q., Dong, C., Nan, X., Li, H., Sun, H., Li, H., Li, P., Hu, Y., 2023. Effect and mechanism of micro-nano aeration treatment on a drip irrigation emitter based on groundwater. Agriculture 13, 2059. https://doi.org/10.3390/agriculture13112059.

Li, H., Hu, L., Song, D., Lin, F., 2014. Characteristics of micro-nano bubbles and potential application in groundwater bioremediation. Water Environ. Res. 86, 844–851. https://doi.org/10.2175/106143014X14062131177953.

Li, Y., Jia, Z., Niu, W., Wang, J., Zhang, M., 2015. Effect of post-infiltration soil aeration at different growth stages on growth and fruit quality of drip-irrigated potted tomato plants (*Solanum lycopersicum*). PLoS One 10, e0143322. https://doi.org/10.1371/journal.pone.0143322.

Li, H., Li, H., Han, Q., Huang, X., Jiang, Y., Sun, H., Li, H., 2020. Influence of micro/nanobubbles on clogging in drip irrigation systems. RSC Adv. 10, 38912–38922. https://doi.org/10.1039/D0RA07782H.

Li, Y., Niu, W., Wang, J., Liu, L., Zhang, M., Xu, J., 2016. Effects of artificial soil aeration volume and frequency on soil enzyme activity and microbial abundance when cultivating greenhouse tomato. Soil Sci. Soc. Am. J. 80, 1208–1221. https://doi.org/10.2136/sssaj2016.06.0164.

Li, M., Qin, Z., Duan, M., Wang, Q., Zhou, B., Weng, H., 2024. Effects of micro-nano bubble water addition on maturation degree and microbial community during aerobic composting. Chemosphere 353, 141657. https://doi.org/10.1016/j.chemosphere.2024.141657.

Li, P., Wang, X., Zhang, C., Chen, K., Junejo, A.R., Liu, J., Li, H., 2025a. Effects of water–fertilizer–gas coupling on emitter clogging and uniformity of drip irrigation system. Horticulturae 11, 333. https://doi.org/10.3390/horticulturae11030333.

Li, Y., Zhang, Z., Wang, J., Zhang, M., 2022. Soil aeration and plastic film mulching increase the yield potential and quality of tomato (*Solanum lycopersicum*). Agriculture 12, 269. https://doi.org/10.3390/agriculture12020269.

Li, Y., Zhou, B., Liu, Y., Jiang, Y., Pei, Y., Shi, Z., 2013. Preliminary surface topographical characteristics of biofilms attached on drip irrigation emitters using reclaimed water. Irrig. Sci. 31, 557–574. https://doi.org/10.1007/s00271-012-0329-1.

Liu, G., Bie, H., Hao, Z., Wang, Y., Ren, W., Hua, Z., 2022. Characteristics of cavitation onset and development in a self-excited fluidic oscillator. Ultrason. Sonochem. 86, 106018. https://doi.org/10.1016/j.ultsonch.2022.106018.

Liu, G., Craig, V.S., 2009. Improved cleaning of hydrophilic protein-coated surfaces using the combination of nanobubbles and SDS. ACS Appl. Mater. Interfaces 1, 481–487. https://doi.org/10.1021/am800150p.

Liu, Y., Zhou, Y., Wang, T., Pan, J., Zhou, B., Muhammad, T., Zhou, C., Li, Y., 2019. Micro-nano bubble water oxygation: synergistically improving irrigation water use efficiency, crop yield and quality. J. Clean. Prod. 222, 835–843. https://doi.org/10.1016/j.jclepro.2019.02.208.

Lv, C., Zhang, E., Gan, H., Niu, W., Ali, S., Dong, A., Zhang, W., Wu, M., Sun, D., 2023. Aerated drip irrigation increased the emitter clogging risk of the Yellow River water drip irrigation. Irrig. Drain. 72, 3–20. https://doi.org/10.1002/ird.2755.

Lyu, T., Wu, S., Mortimer, R.J.G., Pan, G., 2019. Nanobubble technology in environmental engineering: revolutionization potential and challenges. Environ. Sci. Technol. 53, 7175–7176. https://doi.org/10.1021/acs.est.9b02821.

Ma, J., Chen, R., Wen, Y., Zhang, J., Yin, F., Javed, T., Zheng, J., Wang, Z., 2025. Processing tomato (*Lycopersicon esculentum* Miller) yield and quality in arid regions through micro-nano aerated drip irrigation coupled with humic acid application. Agric. Water Manag. 308, 109317. https://doi.org/10.1016/j.agwat.2025.109317.

Mahmoudi, M., Khelil, M.N., Hechmi, S., Latrech, B., Ghrib, R., Boujlben, A., Yacoubi, S., 2022. Effect of surface and subsurface drip irrigation with treated wastewater on soil and water productivity of okra (*Abemoschus esculentus*) crop in semi-arid region of Tunisia. Agriculture 12, 2048. https://doi.org/10.3390/agriculture12122048.

Marcelino, K.R., Wongkiew, S., Shitanaka, T., Surendra, K.C., Song, B., Khanal, S.K., 2023. Micronanobubble aeration enhances plant yield and nitrification in aquaponic systems. ACS EST Eng. 3, 2081–2096. https://doi.org/10.1021/acsestengg.3c00344.

Massee, I., 1913. The sterilisation of seed. Bull. Misc. Inform. (R. Bot. Gard. Kew) 183–187. https://doi.org/10.2307/4107453.

Melsted, S.W., Kurtz, T., Bray, R., 1949. Hydrogen peroxide as an oxygen fertilizer, 97–97 Agron. J. 41. https://doi.org/10.2134/agronj1949.00021962004100020011x.

Mohammadi, S., Mirlatifi, S.M., Homaee, M., Dehghanisanij, H., Hajirad, I., 2024. Evaluation of silage maize production under pulsed drip irrigation in a semi-arid region. Irrig. Sci. 42, 269–283. https://doi.org/10.1007/s00271-023-00880-9.

Molden, D., 2007. Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. International Water Management Institute, Colombo, Earthscan, London.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254–257. https://doi.org/10.1038/nature11420.

Mujtaba, G., Shah, M.U.H., Hai, A., Daud, M., Hayat, M., 2024. A holistic approach to embracing the United Nation's sustainable development goal (SDG-6) towards water security in Pakistan. J. Water Process Eng. 57, 104691. https://doi.org/10.1016/j.jwpe.2023.104691.

Navisa, J., Sravya, T., Swetha, M., Venkatesan, M., 2014. Effect of bubble size on aeration process. Asian J. Sci. Res. 7, 482. https://doi.org/10.3923/ajsr.2014.482.487.

Niu, W., Guo, Q., Zhou, X., Helmers, M.J., 2012. Effect of aeration and soil water redistribution on the air permeability under subsurface drip irrigation. Soil Sci. Soc. Am. J. 76, 815–820. https://doi.org/10.2136/sssaj2011.0329.

Oo, A.Z., Sudo, S., Matsuura, S., Win, K.T., Gonai, T., 2018. Aerated irrigation and pruning residue biochar on N_2O emission, yield and ion uptake of Komatsuna. Horticulturae 4, 33. https://doi.org/10.3390/horticulturae4040033.

Ouyang, Z., Tian, J., Yan, X., Shen, H., 2021. Effects of different concentrations of dissolved oxygen on the growth, photosynthesis, yield and quality of greenhouse tomatoes and changes in soil microorganisms. Agric. Water Manag. 245, 106579. https://doi.org/10.1016/j.agwat.2020.106579.

Ouyang, Z., Tian, J., Yan, X., Yang, Z., 2023. Micro-nano oxygenated irrigation improves the yield and quality of greenhouse cucumbers under-film drip irrigation. Sci. Rep. 13, 19453. https://doi.org/10.1038/s41598-023-45121-3.

Ouyang, Z., Zhang, J., Liang, X., Wang, H., Yang, Z., Tang, R., Yu, Q., Zhang, Y., 2025. Micro-nano aerated subsurface drip irrigation and biochar promote photosynthesis, dry matter accumulation and yield of cucumbers in greenhouse. Agric. Water Manag. 308, 109295. https://doi.org/10.1016/j.agwat.2025.109295.

Panicker, N., Passalacqua, A., Fox, R.O., 2018. On the hyperbolicity of the two-fluid model for gas–liquid bubbly flows. Appl. Math. Model 57, 432–447. https://doi.org/10.1016/j.apm.2018.01.01.

Park, J.S., Ohashi, K., Kurata, K., Lee, J.W., 2010. Promotion of lettuce growth by application of microbubbles in nutrient solution using different rates of electrical conductivity and under periodic intermittent generation in a deep flow technique culture system. Eur. J. Hortic. Sci. 75, 198. https://doi.org/10.1079/ejhs.2010/1861507.

Patle, G.T., Kumar, M., Khanna, M., 2020. Climate-smart water technologies for sustainable agriculture: a review. J. Water Clim. Change 11, 1455–1466. https://doi.org/10.2166/wcc.2019.257.

Pei, Y., Li, Y., Liu, Y., Zhou, B., Shi, Z., Jiang, Y., 2014. Eight emitters clogging characteristics and its suitability under on-site reclaimed water drip irrigation. Irrig. Sci. 32, 141–157. https://doi.org/10.1007/s00271-013-0420-2.

Pendergast, L., Bhattarai, S.P., Midmore, D.J., 2013. Benefits of oxygation of subsurface drip-irrigation water for cotton in a vertosol. Crop Pasture Sci. 64, 1171. https://doi.org/10.1071/CP13348.

Pendergast, L., Bhattarai, S.P., Midmore, D.J., 2019. Evaluation of aerated subsurface drip irrigation on yield, dry weight partitioning and water use efficiency of a broad-acre chickpea (Cicer arietinum, L.) in a vertosol. Agric. Water Manag. 217, 38–46. https://doi.org/10.1016/j.agwat.2019.02.022.

Picologlou, B.F., Characklis, W.G., Zelver, N., 1980. Biofilm growth and hydraulic performance. J. Hydraul. Div. 106, 733–746. https://doi.org/10.1061/JYCEAJ.0005421.

Playán, E., Mateos, L., 2006. Modernization and optimization of irrigation systems to increase water productivity. Agric. Water Manag. 80, 100–116. https://doi.org/10.1016/j.agwat.2005.07.007.

Povilaitis, A., Arablousabet, Y., 2025. Transient effects of air and oxygen nanobubbles on soil moisture retention and soil–substance interactions in compost-amended soil. Water 17 (13), 1923. https://doi.org/10.3390/w17131923.

Pozza, L.E., Field, D.J., 2020. The science of soil security and food security. Soil Secur 1, 100002. https://doi.org/10.1016/j.soisec.2020.100002.

Puig-Bargués, J., Barragán, J., De Cartagena, F.R., 2005. Filtration of effluents for microirrigation systems. Trans. ASAE 48, 969–978. https://doi.org/10.13031/2013.18509.

Qian, Z., Zhuang, S., Gao, J., Tang, L., Harindintwali, J.D., Wang, F., 2022. Aeration increases soil bacterial diversity and nutrient transformation under mulching-induced hypoxic conditions. Sci. Total Environ. 817, 153017. https://doi.org/10.1016/j.scitotenv.2022.153017.

Qiao, W., Luo, Z., Lin, D., Zhang, Z., Wang, S., 2023. An empirical model for aeolian sandy soil wetting front estimation with subsurface drip irrigation. Water 15, 1336. https://doi.org/10.3390/w15071336.

Ramiro, B., de, O., Wasielesky Jr., W., Pimentel, O.A.L.F., Poersch, L.H., da, S., Advent, B., Gonçalves Júnior, G.F., Krummenauer, D., 2024. The effect of using nano and microbubbles as aeration strategies on the nitrification process, microbial community composition, and growth of *Penaeus vannamei* in a super-intensive biofloc system. Aquaculture 587, 740842. https://doi.org/10.1016/j.aquaculture.2024.740842.

Rao, X., Fu, Y., Huang, J., Feng, Y., Wang, Z., 2018. Effects of oxygenated irrigation of cotton and soil fertility. Act. Pedol. Sin. 55. https://doi.org/10.11766/trxb201712290372.

Ravina, I., Paz, E., Sofer, Z., Marcu, A., Shisha, A., Sagi, G., 1992. Control of emitter clogging in drip irrigation with reclaimed wastewater. Irrig. Sci. 13. https://doi.org/10.1007/BF00191055.

Ravina, I., Paz, E., Sofer, Z., Marm, A., Schischa, A., Sagi, G., Yechialy, Z., Lev, Y., 1997. Control of clogging in drip irrigation with stored treated municipal sewage effluent. Agric. Water Manag. 33, 127–137. https://doi.org/10.1016/S0378-3774(96)01286-3.

Rehman, F., Medley, G.J.D., Bandulasena, H., Zimmerman, W.B.J., 2015. Fluidic oscillator-mediated microbubble generation to provide cost effective mass transfer and mixing efficiency to the wastewater treatment plants. Environ. Res. 137, 32–39. https://doi.org/10.1016/j.envres.2014.11.01.

Sakr, M., Mohamed, M.M., Maraqa, M.A., Hamouda, M.A., Aly Hassan, A., Ali, J., Jung, J., 2022. A critical review of the recent developments in micro–nano bubbles applications for domestic and industrial wastewater treatment. Alex. Eng. J. 61, 6591–6612. https://doi.org/10.1016/j.aej.2021.11.041.

Sanchis-Ibor, C., Ortega-Reig, M., Guillem-García, A., Carricondo, J.M., Manzano-Juárez, J., García-Mollá, M., Royuela, Á., 2021. Irrigation post-modernization. farmers envisioning irrigation policy in the region of Valencia (Spain). Agriculture 11, 317. https://doi.org/10.3390/agriculture11040317.

Sang, H., Jiao, X., Wang, S., Guo, W., Salahou, M.K., Liu, K., 2018. Effects of micro-nano bubble aerated irrigation and nitrogen fertilizer level on tillering, nitrogen uptake and utilization of early rice. Plant Soil Environ. 64, 297–302. https://doi.org/10.17221/240/2018-PSE.

Scott, H.D., Renaud, F.G., 2015. Aeration and drainage. In: Lascano, Robert J., Sojka, R. E. (Eds.), Irrigation of Agricultural Crops, second ed. the American Society of Agronomy, Inc. / Crop Science Society of America, Inc. / Soil Science Society of America, Inc, Madison, pp. 195–236. https://doi.org/10.2134/agronmonogr30.2ed.c7.

Shanthi, C., Pappa, N., 2017. An artificial intelligence based improved classification of two-phase flow patterns with feature extracted from acquired images. ISA Trans. 68, 425–432. https://doi.org/10.1016/j.isatra.2016.10.021.

Shi, K., Lu, T., Zheng, W., Zhang, X., Zhangzhong, L., 2022. A review of the category, mechanism, and controlling methods of chemical clogging in drip irrigation system. Agriculture 12, 202. https://doi.org/10.3390/agriculture12020202.

Skiba, U., Ball, B., 2002. The effect of soil texture and soil drainage on emissions of nitric oxide and nitrous oxide. Soil Use Manag. 18, 56–60. https://doi.org/10.1111/j.1475-2743.2002.tb00050.x.

Smith, S., De Smet, I., 2012. Root system architecture: insights from *Arabidopsis* and cereal crops. Philos. Trans. R. Soc. B Biol. Sci. 367, 1441–1452. https://doi.org/10.1098/rstb.2011.0234.

Snell, J.R., Zhou, C., Carpenter, J.F., Randolph, T.W., 2016. Particle formation and aggregation of a therapeutic protein in nanobubble suspensions. J. Pharm. Sci. 105, 3057–3063. https://doi.org/10.1016/j.xphs.2016.06.020.

Stepanova, A.Y., Polyakova, L.I., Dolgikh, Y.I., Vartapetian, B.B., 2002. The response of sugarcane (*saccharum officinarum*) cultured cells to anoxia and the selection of a tolerant cell line. Russ. J. Plant Physiol. 49, 406–412. https://doi.org/10.1023/A:1015509506293.

Su, N., Midmore, D.J., 2005. Two-phase flow of water and air during aerated subsurface drip irrigation. J. Hydrol. 313, 158–165. https://doi.org/10.1016/j.jhydrol.2005.02.025.

Sun, C., Wang, D., Liu, H., Xiao, Y., Guo, W., Liu, B., 2024. Simulation and optimization of the throttle releaser in aerated irrigation systems. Agriculture 14, 1248. https://doi.org/10.3390/agriculture14081248.

Sun, S., Wu, P., Wang, Y., Zhao, X., Liu, J., Zhang, X., 2013. The impacts of interannual climate variability and agricultural inputs on water footprint of crop production in an irrigation district of China. Sci. Total Environ. 444, 498–507. https://doi.org/10.1016/j.scitotenv.2012.12.016.

Sung, M., Teng, C.H., Yang, T.H., 2017. Dissolution enhancement and mathematical modeling of removal of residual trichloroethene in sands by ozonation during flushing with micro-nano-bubble solution. J. Contam. Hydrol. 202, 1–10. https://doi.org/10.1016/j.jconhyd.2017.03.008.

Taft, H.L., 2015. Water scarcity: global challenges for agriculture in. Food, Energy, and Water. Elsevier, pp. 395–429. https://doi.org/10.1016/B978-0-12-800211-7.00016-8.

Takahashi, M., 2005. ζ potential of microbubbles in aqueous solutions: electrical properties of the gas−water interface. J. Phys. Chem. B 109, 21858–21864. https://doi.org/10.1021/jp0445270.

Takahashi, M., Kawamura, T., Yamamoto, Y., Ohnari, H., Himuro, S., Shakutsui, H., 2003. Effect of shrinking microbubble on gas hydrate formation. J. Phys. Chem. B 107, 2171–2173. https://doi.org/10.1021/jp022210z.

Tan, B.H., An, H., Ohl, C.D., 2020. How bulk nanobubbles might survive. Phys. Rev. Lett. 124, 134503. https://doi.org/10.1103/PhysRevLett.124.134503.

Tang, L., Shaikh, I.A., Tunio, A., Junejo, A.R., Hao, L., Dahri, J., Mangrio, M.A., Soothar, R.K., Khan, Z.A., 2024. Effect of raised flat bed and ridge planting on wheat crop growth and yield under varying soil moisture depletions. Agronomy 14, 1404. https://doi.org/10.3390/agronomy14071404.

Tarchitzky, J., Rimon, A., Kenig, E., Dosoretz, C.G., Chen, Y., 2013. Biological and chemical fouling in drip irrigation systems utilizing treated wastewater. Irrig. Sci. 31, 1277–1288. https://doi.org/10.1007/s00271-013-0406-0.

Taylor, H., Bastos, R., Pearson, H., Mara, D., 1995. Drip irrigation with waste stabilisation pond effluents: solving the problem of emitter fouling. Water Sci. Technol. 31. https://doi.org/10.1016/0273-1223(95)00528-U.

Tesař, V., 2024. Fluidic Oscillators and their Applications. Cambridge Scholars Publishing, UK, p. 365.

Thani, Q.A., Schaffer, B., Liu, G., Vargas, A.I., Crane, J.H., 2016. Chemical oxygen fertilization reduces stress and increases recovery and survival of flooded papaya (*Carica papaya* L.) plants. Sci. Hortic. 202, 173–183. https://doi.org/10.1016/j.scienta.2016.03.004.

Thomas, P.G., 2021. Optimisation of Stabilised Hydrogen Peroxide Use for Drip Irrigation [PhD thesis]. Central Queensland University, Australia. ⟨https://acquire.cqu.edu.au/articles/thesis/Optimisation_of_stabilised_hydrogen_peroxide_use_for_drip_irrigation/20288844?file=36239739⟩.

Thomas, P.G., Bhattarai, S.P., Balsys, R.J., Walsh, K.B., Midmore, D.J., 2025. Continuous injection of hydrogen peroxide in drip irrigation—application to field crops. Agronomy 15, 385. https://doi.org/10.3390/agronomy15020385.

Torabi, M., Midmore, D.J., Walsh, K.B., Bhattarai, S.P., Tait, L., 2013. Analysis of factors affecting the availability of air bubbles to subsurface drip irrigation emitters during oxygation. Irrig. Sci. 31, 621–630. https://doi.org/10.1007/s00271-012-0337-1.

Torabi, M., Midmore, D.J., Walsh, K.B., Bhattarai, S.P., 2014. Improving the uniformity of emitter air bubble delivery during oxygation. J. Irrig. Drain. Eng. 140, 06014002. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000735.

Torabi, M., Miranzadeh, M., 2021. Enhancing the uniformity of emitter air bubble delivery during irrigation with aerated water. Water Resour. Eng. 14, 1–15. https://doi.org/10.30495/wej.2021.4585.

Van Dijk, M., Morley, T., Rau, M.L., Saghai, Y., 2021. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. Nat. Food 2, 494–501. https://doi.org/10.1038/s43016-021-00322-9.

Van Lanen, H.A.J., Reinds, G.J., Boersma, O.H., Bouma, J., 1992. Impact of soil management systems on soil structure and physical properties in a clay loam soil, and the simulated effects on water deficits, soil aeration and workability. Soil Tillage Res 23, 203–220. https://doi.org/10.1016/0167-1987(92)90101-G.

Vartapetian, B.B., Dolgikh, Y.I., Polyakova, L.I., Chichkova, N.V., Vartapetian, A.B., 2014. Biotechnological approaches to creation of hypoxia and anoxia tolerant plants. Acta Nat. 6, 19–30. https://doi.org/10.32607/20758251-2014-6-2-19-30.

Vinci, G., Savastano, M., Restuccia, D., Ruggeri, M., 2025. Nanobiopesticides: sustainability aspects and safety concerns. Environments 12, 74. https://doi.org/10.3390/environments12030074.

Wang, J., Cui, Y., Wu, K., Wu, S., Wu, K., Li, Y., Niu, W., 2024d. Micro/nanobubble-aerated drip irrigation affects saline soil microenvironments and tomato growth by altering bacterial communities. Soil Tillage Res. 239, 106034. https://doi.org/10.1016/j.still.2024.106034.

Wang, J., Dong, X., Zhu, L., Zhou, Z., 2024a. Theoretical and experimental investigation on a novel cavitation-assisted abrasive flow polishing method. Micromachines 15, 1142. https://doi.org/10.3390/mi15091142.

Wang, J., Guo, X., Zhao, Q., Chen, R., Li, G., Zhou, B., Cheng, P., 2025a. Subsurface drip irrigation with micro-nano bubble hydrogen water improves the salt tolerance of lettuce by regulating the antioxidant system and soil bacterial community. Appl. Soil Ecol. 207, 105948. https://doi.org/10.1016/j.apsoil.2025.105948.

Wang, J., He, Q., Cao, K., Zhou, B., Niu, X., Wang, D., Chen, R., Zheng, Z., 2023a. Micro-nano bubble water with potassium fertigation improves strawberry yield and quality by changing soil bacterial community. Rhizosphere 28, 100783. https://doi.org/10.1016/j.rhisph.2023.100783.

Wang, Y., Lei, H., Zhang, Z., Shi, W., 2022. Effects of aerated subsurface drip irrigation on rhizosphere soil environment and pepper (*Capsicum annum* L.) growth in three soil types. Arch. Agron. Soil Sci. 69, 1027–1038. https://doi.org/10.1080/03650340.2022.2049766.

Wang, S., Liu, Y., Li, P., Wang, Y., Yang, J., Zhang, W., 2020. Micro-nanobubble aeration promotes senescence of submerged macrophytes with low total antioxidant capacity in urban landscape water. Environ. Sci. Water Res. Technol. 6, 523–531. https://doi.org/10.1039/C9EW00929A.

Wang, Y., Liu, N., Zhang, J., Jin, Y., Zhang, J., Wang, Z., 2024c. Effects of aeration on hydraulic and anti-clogging performance of subsurface drip irrigation emitters. Irrig. Sci. https://doi.org/10.1007/s00271-024-00953-3.

Wang, C., Lu, Y., Song, L., Wang, J., Zhu, Y., Ma, J., Zheng, J., 2025b. Integrated effects of warming irrigation, aeration, and humic acid on yield, quality, and GHG emissions in processing tomatoes in xinjiang. Agronomy 15, 1353. https://doi.org/10.3390/agronomy15061353.

Wang, J., Niu, W., Song, X., Han, J., 2023b. Response of tomato root endophytic bacterial communities to water-oxygen coupling under micro/nanoaerated drip irrigation in slightly saline soils. Sci. Hortic. 321, 112281. https://doi.org/10.1016/j.scienta.2023.112281.

Wang, Y., Shi, W., Jing, B., Liu, L., 2024b. Modulation of soil aeration and antioxidant defenses with hydrogen peroxide improves the growth of winter wheat (*Triticum aestivum* L.) plants. J. Clean. Prod. 435, 140565. https://doi.org/10.1016/j.jclepro.2024.140565.

Wang, Y., Wang, S., Sun, J., Dai, H., Zhang, B., Xiang, W., Z., Li, P., Yang, J., Zhang, W., 2021b. Nanobubbles promote nutrient utilization and plant growth in rice by upregulating nutrient uptake genes and stimulating growth hormone production. Sci. Total Environ. 800, 149627. https://doi.org/10.1016/j.scitotenv.2021.149627.

Wang, T., Wang, Z., Zhang, J., Ma, K., 2023c. Application effect of different oxygenation methods with mulched drip irrigation system in Xinjiang. Agric. Water Manag. 275, 108024. https://doi.org/10.1016/j.agwat.2022.108024.

Wang, L., Wu, W., Xiao, J., Huang, Q., Hu, Y., 2021a. Effects of different drip irrigation modes on water use efficiency of pear trees in Northern China. Agric. Water Manag. 245, 106660. https://doi.org/10.1016/j.agwat.2020.106660.

Wang, W., Zhang, X., Li, C., Zou, Y., Li, G., Chen, Y., Chen, G., Duan, J., 2023d. Bubble behavior, flow characteristics, and mass transfer enhancement in self-priming venturi tubes. Chem. Eng. Sci. 270, 118536. https://doi.org/10.1016/j.ces.2023.118536.

Wei, M., Shi, Y., Yang, Q., Liang, J., 2025. Oxygenated subsurface drip irrigation and organic fertilizer increase the yield and quality of *P. notoginseng* by improving soil microenvironment. Soil Use Manag. 41, e13156. https://doi.org/10.1111/sum.13156.

Wu, Y., Lyu, T., Yue, B., Tonoli, E., Verderio, E.A.M., Ma, Y., Pan, G., 2019. Enhancement of tomato plant growth and productivity in organic farming by agri-nanotechnology using nanobubble oxygation. J. Agric. Food Chem. 67, 10823–10831. https://doi.org/10.1021/acs.jafc.9b04117.

Wu, C., Nesset, K., Masliyah, J., Xu, Z., 2012. Generation and characterization of submicron size bubbles. Adv. Colloid Interface Sci. 179, 123–132. https://doi.org/10.1016/j.cis.2012.06.012.

Wu, M., Zhang, J., Wang, Z., Zhu, Y., Song, L., Zong, R., Han, Y., 2022. Effects of aerated drip irrigation and degradable film mulching on growth and water use of maize. Chin. J. Eco Agric. 30, 1425–1438. https://doi.org/10.12357/cjea.20220027.

Xiao, Y., Jiang, S.C., Wang, X., Muhammad, T., Song, P., Zhou, B., Zhou, Y., Li, Y., 2020. Mitigation of biofouling in agricultural water distribution systems with nanobubbles. Environ. Int. 141, 105787. https://doi.org/10.1016/j.envint.2020.105787.

Yin, J., Li, J., Li, H., Liu, W., Wang, D., 2015. Experimental study on the bubble generation characteristics for an venturi type bubble generator. Int. J. Heat. Mass Transf. 91, 218–224. https://doi.org/10.1016/j.ijheatmasstransfer.2015.05.076.

Yu, Z., Wang, H., Yu, D., Yin, N., Zhang, J., 2024. The effect of aeration and irrigation on the improvement of soil environment and yield in dryland maize. Front. Plant Sci. 15, 1464624. https://doi.org/10.3389/fpls.2024.1464624.

Yuan, L., Wenquan, N., Jingwei, W., Jian, X., Mingzhi, Z., Kangyong, L., 2016. Review on advances of airjection irrigation. Int. J. Agric. Biol. Eng. 9, 1–10.

Zhang, Q., Niu, W.Q., Du, Y.D., Cui, B.J., 2019. Effects of aerated irrigation on CO_2 and N_2O emission from protected melon soils under different nitrogen application levels. J. Appl. Ecol. 30, 1319–1326. https://doi.org/10.13287/j.1001-9332.201904.027.

Zhang, M., Qiu, L., Liu, G., 2020. Basic characteristics and application of micro-nano bubbles in water treatment. IOP Conf. Ser. Earth Environ. Sci. 510, 042050. https://doi.org/10.1088/1755-1315/510/4/042050.

Zhang, Z.-H., Wang, S., Cheng, L., Ma, H., Gao, X., Brennan, C.S., Yan, J.-K., 2023. Micro-nano-bubble technology and its applications in food industry: a critical review. Food Rev. Int. 39, 4213–4235. https://doi.org/10.1080/87559129.2021.2023172.

Zhang, Q., Zhang, P., Deng, Y., Sun, C., Tian, X., Si, B., Li, B., Guo, X., Liu, F., Zhang, Z., 2022. Study on regulation mechanism of tomato root growth in greenhouse under cycle aerated subsurface drip irrigation. Agronomy 12, 2609. https://doi.org/10.3390/agronomy12112609.

Zhao, H., Li, L., Fan, G., Xie, S., Li, F., 2023. Effects of aerated brackish water irrigation on growth of *Lycium barbarum* seedlings. Sci. Hortic. 310, 111721. https://doi.org/10.1016/j.scienta.2022.111721.

Zhao, F., Yang, X., Dong, M., Jiang, Y., Yu, S., 2017. Aerated irrigation improves the chemical characteristics and bacterial community structure of grape rhizosphere soil in arid areas. Trans. Chin. Soc. Agric. Eng. 33, 119. https://doi.org/10.11975/j.issn.1002-6819.2017.22.015.

Zhou, Y., Bastida, F., Liu, Y., He, J., Chen, W., Wang, X., Xiao, Y., Song, P., Li, Y., 2022. Impacts and mechanisms of nanobubbles level in drip irrigation system on soil fertility, water use efficiency and crop production: the perspective of soil microbial community. J. Clean. Prod. 333, 130050. https://doi.org/10.1016/j.jclepro.2021.130050.

Zhou, Y., He, J., Liu, Y., Liu, H., Wang, T., Liu, Y., Chen, W., Muhammad, T., Li, Y., 2023. Aerated drip irrigation improves watermelon yield, quality, water and fertilizer use efficiency by changing plant biomass and nutrient partitioning. Irrig. Sci. 41, 739–748. https://doi.org/10.1007/s00271-023-00853-y.

Zhou, B., Li, Y., Liu, Y., Pei, Y., Jiang, Y., Liu, H., 2014. Effects of flow path depth on emitter clogging and surface topographical characteristics of biofilms. Irrig. Drain. 63, 46–58. https://doi.org/10.1002/ird.1792.

Zhou, Y-P, Zhou, B., Xu, F-P., Muhammad, T., Li, Y-K., 2019. Appropriate dissolved oxygen concentration and application stage of micro-nano bubble water oxygation in greenhouse crop plantation. Agric. Water Manag 223. https://doi.org/10.1016/j.agwat.2019.105713.

Zhu, Y., Cai, H., Song, L., Hou, H., Chen, H., 2016. Effects of climatic factors and soil parameters on soil respiration under oxygation condition. J. Agric. Mach. 47, 223–232. https://doi.org/10.6041/j.issn.1000-1298.2016.12.027.

Zhu, Y., Cai, H., Song, L., Wang, X., Shang, Z., Sun, Y., 2020. Aerated irrigation of different irrigation levels and subsurface dripper depths affects fruit yield, quality and water use efficiency of greenhouse tomato. Sustainability 12, 2703. https://doi.org/10.3390/su12072703.

Zhu, Y., Dyck, M., Cai, H., Song, L., Chen, H., 2019. The effects of aerated irrigation on soil respiration, oxygen, and porosity. J. Integr. Agric. 18, 2854–2868. https://doi.org/10.1016/S2095-3119(19)62618-3.

Zhu, J., Niu, W., Du, Y., Zhang, Z., Yang, R., Siddique, K.H.M., Sun, J., 2024. Deciphering the microbial functional potential of aeration drip irrigation to enhance soil organic

carbon content. Pedosphere, S1002016024000158. https://doi.org/10.1016/j.pedsph.2024.03.002.
Zhu, M., Wang, Q., Sun, Y., Zhang, J., 2021. Effects of oxygenated blackish water on germination and growth characteristics of wheat. Agric. Water Manag 245, 106520. https://doi.org/10.1016/j.agwat.2020.106520.
Zhu, J., Xu, N., Siddique, K.H.M., Zhang, Z., Niu, W., 2022. Aerated drip irrigation improves water and nitrogen uptake efficiencies of tomato roots with associated changes in the antioxidant system. Sci. Hortic. 306, 111471. https://doi.org/10.1016/j.scienta.2022.111471.
Zhu, L., Yu, S., Jin, Q., 2012. Effects of aerated irrigation on leaf senescence at late growth stage and grain yield of rice. Rice Sci. 19, 44–48. https://doi.org/10.1016/S1672-6308(12)60019-5.