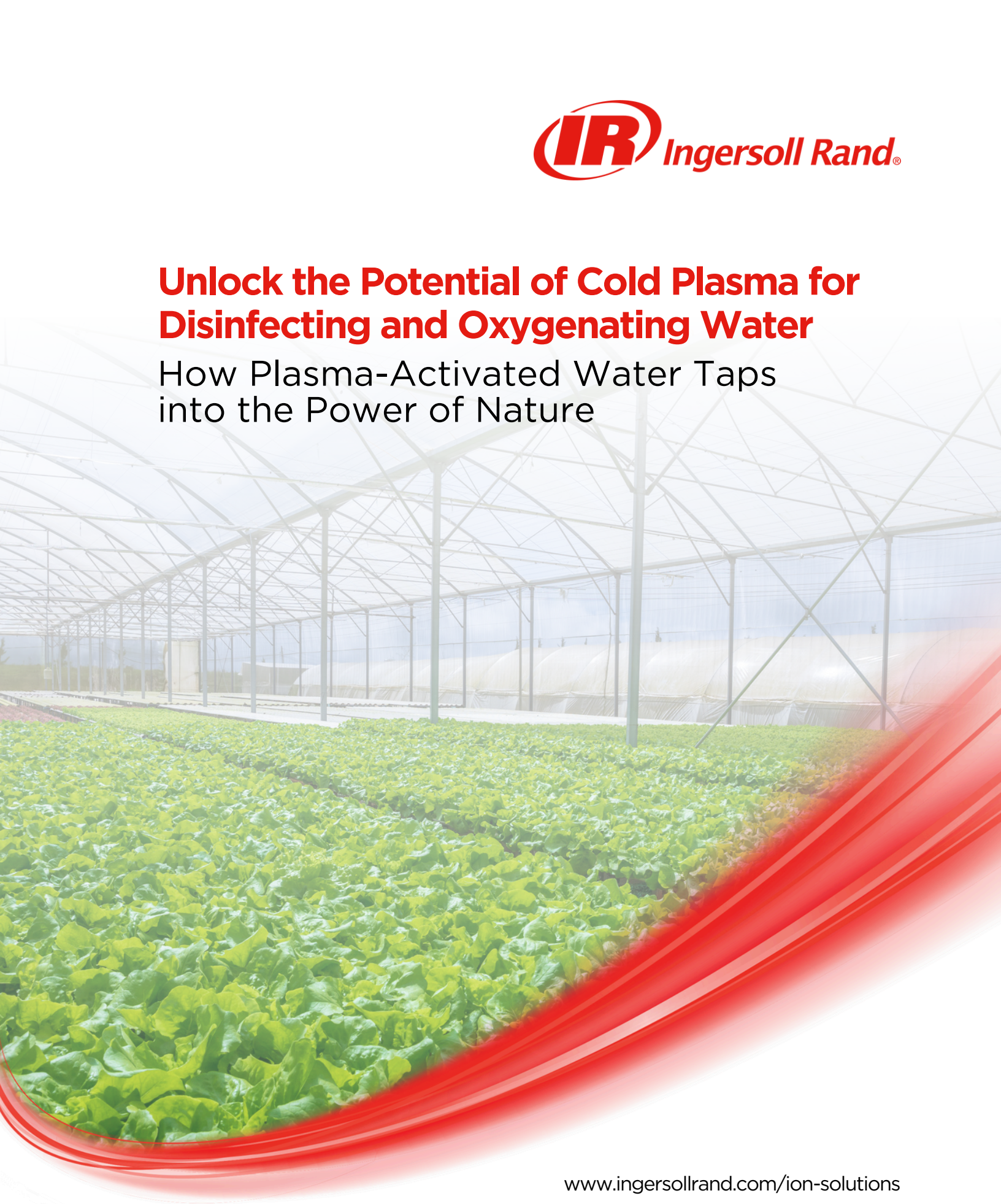
Unlock the Potential of Cold Plasma for Disinfecting and Oxygenating Water

How Plasma-Activated Water Taps into the Power of Nature



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Introduction to Cold Plasma Technology

Thanks to its unique properties, cold plasma has become a focal point for innovation and research in recent years, particularly in the agricultural and food industries. Indeed, one of the most revolutionary new developments in cold plasma technology is the creation of plasma-activated water to provide disinfection and oxygenation in controlled environment agriculture (CEA) and indoor farming applications.

Cold plasma technology taps into the power of nature to create reactive oxygen species which have been shown to boost plant health, disinfect without the use of synthetic chemicals, mitigate pathogens and reduce chemical dependence. Through the use of plasma-activated water, CEA operations can get closer to their sustainability goals, reduce chemical dependence.

Cold Plasma for Indoor Growing

At present, the CEA industry faces a number of influential macro trends: an expanding global population, increased food safety and security legislation, growing consumer preference for local and organic produce, and a booming market for specialty crops, including hemp and cannabis. Meeting these demands sustainably will require the industry as a whole to embrace new innovations that allow their operations to produce more food with fewer resources and less impact on the environment—all while remaining profitable. In order to do so, they must tackle the following areas of focus:

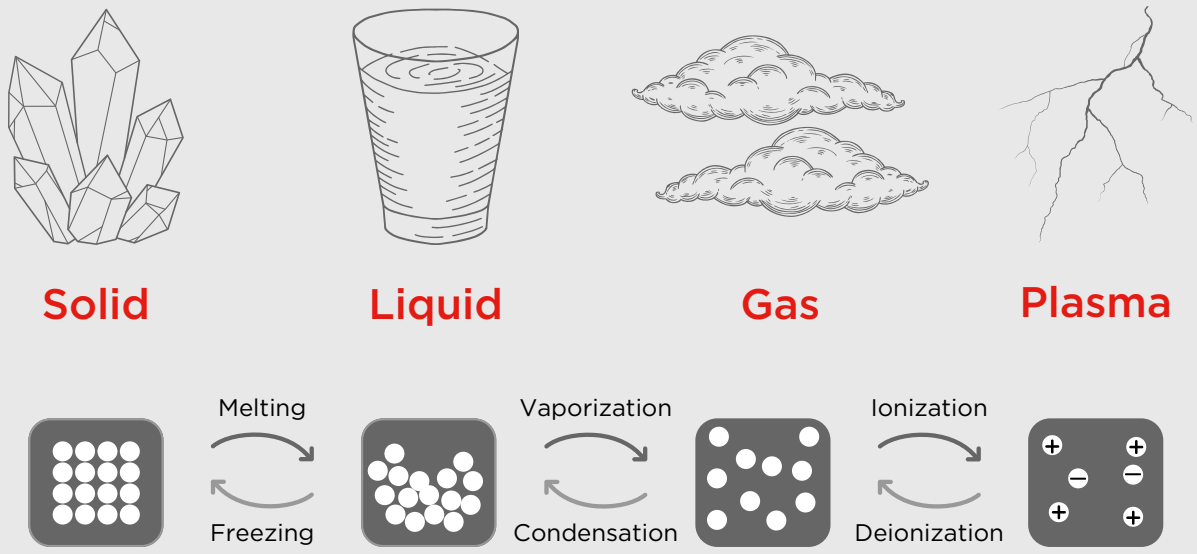
- Improved water quality
- Biofilm prevention
- Plant resilience
- Energy efficiency
- Pathogen mitigation
- Sustainability goals
- Increased oxygenation
- Decreased reliance on chemicals

Given these focus areas, cold plasma technology is an exciting development for the CEA industry. Treating water with cold plasma results in plasma-activated water (PAW), which has distinct qualities such as oxygenation, thanks to its high content of dissolved oxygen. Strategic application and the use of PAW can reduce overhead costs, prevent biofilm, and improve hygiene across operations.

Unlocking Nature's Best-Kept Secret: Cold Plasma

Plasma can be observed everywhere: the Earth's auroras, lightning strikes and within stars[1]. Yet despite its ubiquity in the natural world, plasma is rarely mentioned alongside the other states of matter—solid, liquid and gas.

The Four States of Matter



For those unfamiliar with the mechanics of plasma, it is an ionized gas. Ionization occurs when one or more electrons are torn free from a molecule or an atom, leaving positively charged ions and negatively charged electrons. These unique properties allow technologies that generate plasma to accomplish more efficient chemical reactions. For example, thermal plasmas are useful for industrial applications such as welding, power-cutting and steel-making.

[1] Plasma | Center for Science Education. https://scied.ucar.edu/learning-zone/sun-space-weather/plasma. Accessed 16 May 2022.

Examples of cold, or non-thermal, plasma applications: fluorescent light bulbs and neon signs

While thermal plasmas can reach temperatures of up to several thousand degrees Celsius[1], technologies that create cold, or non-thermal, plasma use electron acceleration versus heat to ionize the gas. This cold plasma processes allow this technology to accomplish efficient chemical reactions while generally remaining at or near ambient temperature. Well-known examples include fluorescent lights and neon signs, but cold plasma has been used in a number of different industries for decades.

In agriculture, plasma technologies have demonstrated their potential in a number of applications, including the chemical and biological decontamination of products, processing tools and packaging, the cleaning and purifying of air and water, the production of fertilizers, the decontamination of seeds and the enhancement of their germination[2], [3]. The PAW production model is not chemical-reliant, making plasma-activated water much more eco-friendly than some traditional approaches in CEA[4].

[1] Lieberman, Michael A., and Allan J. Lichtenberg. Principles of Plasma Discharges and Materials Processing, Second Edition. John Wiley & Sons, Inc., 2005. DOI.org (Crossref), https://doi.org/10.1002/0471724254.
[2] Brandenburg, Ronny. Dielectric Barrier Discharges: Progress on Plasma Sources and on the Understanding of Regimes and Single Filaments. IOP Publishing LTD, 2017.
[3] Thirumdas, Rohit. Exploitation of Cold Plasma Technology for Enhancement of Seed Germination. Agricultural Research & Technology: Open Access Journal, 2018. 13. 10.19080/ARTOAJ.2018.13.555874.
[4] Kakati, Bharat & Bujarbarua, Sakhee & Bora, Dhiraj. An Eco-Friendly, Pollution-Free Process for Seed Germination and Plant Yield. AIP Conference Proceedings, 2019. 2091. 020021. 10.1063/1.5096512.

While the use of cold plasma for agriculture is not novel, new applications for this technology are budding in water oxygenation and disinfection for CEA and indoor farming. In fact, Ingersoll Rand Ion Solutions technology uses cold plasma to enhance the very nature of water. The patented process injects nanobubbles containing high levels of dissolved oxygen (DO) and increased oxidation reduction potential (ORP), generating high-quality plasma-activated water with dual benefits:

Ingersoll Rand Ion Solutions

- Energy-efficient, long-lasting oxygenation for healthy water quality
- Disinfecting advanced oxidation process (AOP) capable of mitigating not only organic bacteria and pathogens but also inorganic pollutants

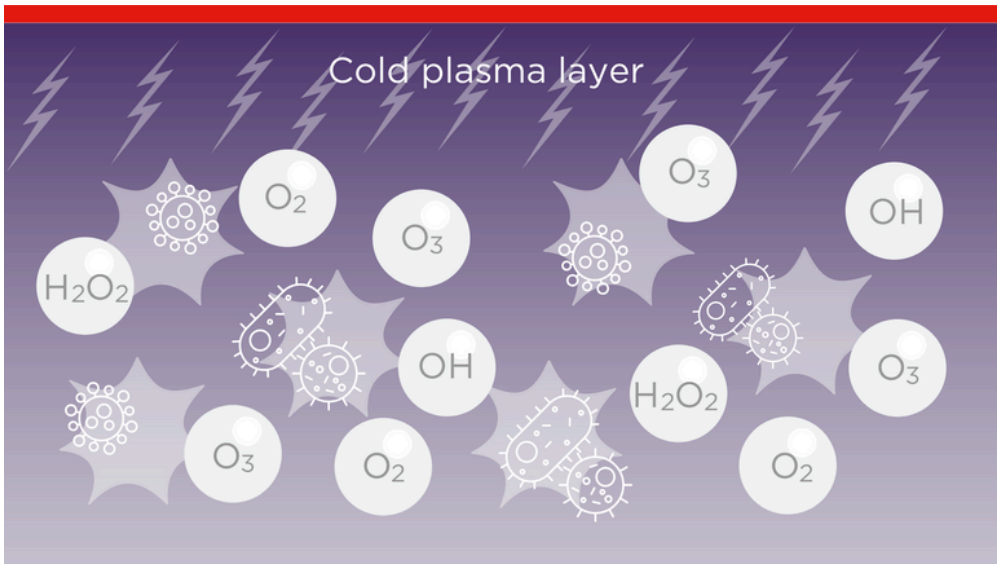
The Ingersoll Rand Ion Solutions nanobubble injection process involves a simple but transformational plug-and-play system: Water flows into a chamber in a specialized piece of equipment where patented hardware and software establish a layer of cold plasma within an oxygen “cloud.” The cold plasma in turn creates positively charged ions, which are drawn via electromotive force to an electrode under a sheet of water within the chamber. These ions rapidly pass through the water toward this electrode and become nanobubbles of oxygen gas that stay suspended in the liquid. Naturally occurring reactive oxygen species (ROS)—key for disinfection—are also added to the water in controlled doses.

[1] Brandenburg, Ronny. Dielectric Barrier Discharges: Progress on Plasma Sources and on the Understanding of Regimes and Single Filaments. IOP Publishing LTD, 2017.
[2] Thirumdas, Rohit. Exploitation of Cold Plasma Technology for Enhancement of Seed Germination. Agricultural Research & Technology: Open Access Journal, 2018. 13. 10.19080/ARTOAJ.2018.13.555874.
[3] Kakati, Bharat & Bujarbarua, Sakhee & Bora, Dhiraj. An Eco-Friendly, Pollution-Free Process for Seed Germination and Plant Yield. AIP Conference Proceedings, 2019. 2091. 020021. 10.1063/1.5096512.

These innovative features make Ion Solutions the first system capable of oxygenating and adding disinfecting compounds to water using only air and electricity as inputs.

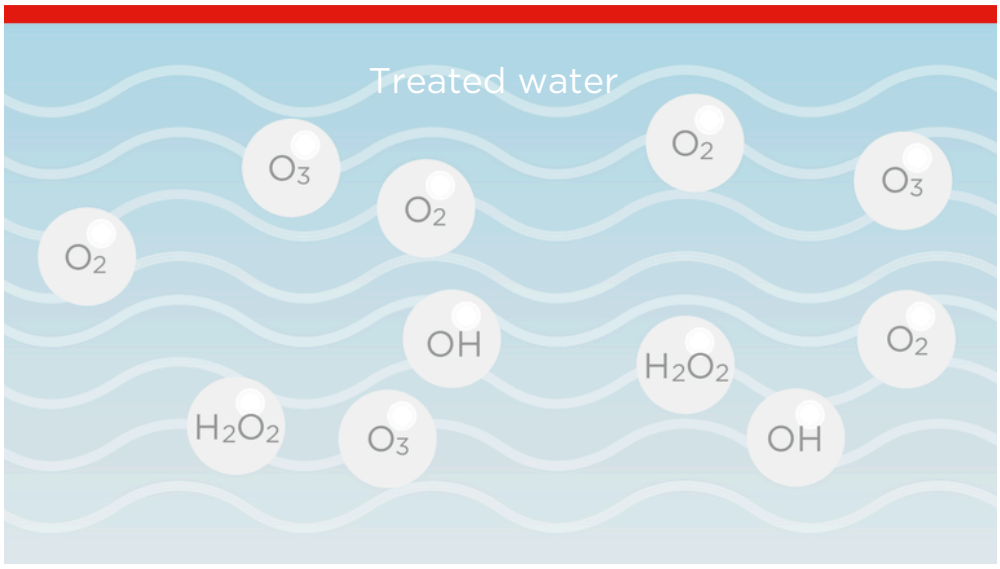
Plasma Injection Process

During the Ion Solutions ultra-fine bubble (UFB) injection process where dissolved oxygen (DO) and reactive oxygen species (ROS) are added to water



Plasma Activated Water

Plasma-activated water (PAW): the outcome of the UFB injection process



Disinfection and Reactive Oxygen Species

A notable benefit of plasma-activated water is its applications for organic disinfection free of synthetic chemicals.

The Ion Solutions system facilitates not only the injection of dissolved oxygen, but it can also inject Reactive Oxygen Species (ROS) in a highly controlled manner, resulting in an Advanced Oxidation Process (AOP) for highly effective pathogen mitigation.

ROS are the most powerful, naturally occurring disinfecting compounds on Earth. These oxidizing agents mitigate organic bacteria and pathogens as well as inorganic pollutants, helping to fight disease, pests, biofilm and algae in CEA facilities without harsh chemicals and without affecting nutrient solution mixtures.

Utilizing AOP reduces or eliminates altogether the need for synthetic chemicals to treat water. CEA cultivators typically depend on a variety of chemical inputs to increase water's oxidation reduction potential (ORP), which fights bacteria such as E. coli, Salmonella, Listeria and Pythium. Water with elevated ORP also helps control algae growth, hygienically washes fruits and vegetables and disinfects equipment[1].

While useful for disinfection, the synthetic chemicals traditionally used in the process of increasing water ORP can, among other potential risks, leave harmful residues that affect human health. The use of ROS is shown to be effective at obtaining disinfection levels of 800 millivolts (mV) that inactivate or destroy bacteria previously possible only through the use of harsh chemicals[2].

[1] Xu Y, Tian Y, Ma R, Liu Q, Zhang J. Effect of Plasma Activated Water on the Postharvest Quality of Button Mushrooms, Agaricus Bisporus. Food Chem. 2016 Apr 15;197(Pt A):436-44. doi: 10.1016/j.foodchem.2015.10.144. PMID: 26616972.
[2] Mai-Prochnow, A., Zhou, R., Zhang, T. et al. Interactions of Plasma-Activated Water With Biofilms: Inactivation, Dispersal Effects and Mechanisms of Action. npj Biofilms and Microbiomes 7, 11 (2021). https://doi.org/10.1038/s41522-020-00180-6.

Water Oxygenation

Higher amounts of dissolved oxygen (DO) in irrigation water help plants thrive. Research has shown that higher DO levels are correlated with increased growth, improved photosynthetic ability, larger yields and even the increased nutritional value of plants.[1]

As CEA operators understand profoundly, oxygen is a fundamental component of plant growth processes. Research has shown that reduced concentrations of DO in the root zone can lead to changes in plant metabolism to avoid internal anoxia[2]. This adaptive respiration restriction affects a wide range of biosynthetic functions and can negatively affect plant health.

Irrigation water with high levels of DO significantly improves plant resistance to stress and diseases: Research showed that tomato plants inoculated with PythiumF707 (a root rot pathogen) experienced a significant decrease in root colonization by the pathogen when treated with water enhanced with oxygen[1].

Indeed, higher levels of DO in water have direct, measurable effects on plant health and yield. Beneficial microbes, found in root zones, thrive in the presence of oxygen. The more oxygen there is in irrigation water applied to root zones, the faster these beneficial microbes reproduce, and the more they help plants uptake key nutrients such as nitrogen.

[1] Ouyang, Zan, et al. Effects of Different Concentrations of Dissolved Oxygen or Temperatures on the Growth, Photosynthesis, Yield and Quality of Lettuce. Agricultural Water Management, vol. 228, Feb. 2020, p. 105896. ScienceDirect, https://doi.org/10.1016/j.agwat.2019.105896.
[2] Geigenberger, P. Response of Plant Metabolism to Too Little Oxygen. Curr Opin Plant Biol. Jun. 2003, 6(3):247-56. doi: 10.1016/s1369-5266(03)00038-4. PMID: 12753974.
[3] Chérif, M., et al. Effect of Oxygen Concentration on Plant Growth, Lipidperoxidation, and Receptivity of Tomato Roots to Pythium F under Hydroponic Conditions. European Journal of Plant Pathology, vol. 103, no. 3, Mar. 1997, pp. 255–64. Springer, https://doi.org/10.1023/A:1008691226213.

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Ultra-Fine Bubbles (UFB)

A study on rice production recorded a remarkable 6.75%-10.79% accumulation increase of nitrogen in early rice plant growth with the use of DO-rich water[1]. This characteristic of plasma-activated water has the added benefits of the more efficient use of—and reduced dependence on—fertilizers and other resource inputs.

Additionally, water with high levels of DO is correlated with increases in dry weight of plant biomass. Study findings showed a significant increase in dry weight in lettuce treated with high-DO water compared with controls, even in a growing facility with cooler temperatures[2].

DO helps with water uptake and boosts plant resilience throughout their lifecycle. Research further indicated that pre-treatment of seeds with plasma-activated water resulted in increased length of seedlings. Many cannabis cultivators have reported significant increases in both dried weight and flower yield with DO levels of at least 20-30 ppm[3].

However, tap water alone is unlikely to contain enough DO to meet growers' needs. Due to concerns about high oxygen levels corroding pipes as well as site-specific temperature differences, municipal tap water typically contains low amounts of DO. For example, fresh water at sea level saturates at about 9.1 ppm DO at 68 degrees Fahrenheit, and about 7.6 ppm at 86 degrees Fahrenheit[4]. To bridge any gap between existing and desired DO levels for irrigation purposes, CEA professionals deploy a variety of techniques and solutions, such as air stones, diffusers or higher-tech equipment that injects air bubbles directly into water. However, obtaining consistent, long-lasting DO levels with these methods can be challenging—especially taking into account that water used in agriculture is commonly stored and used at warmer temperatures and therefore more difficult to consistently and reliably oxygenate.

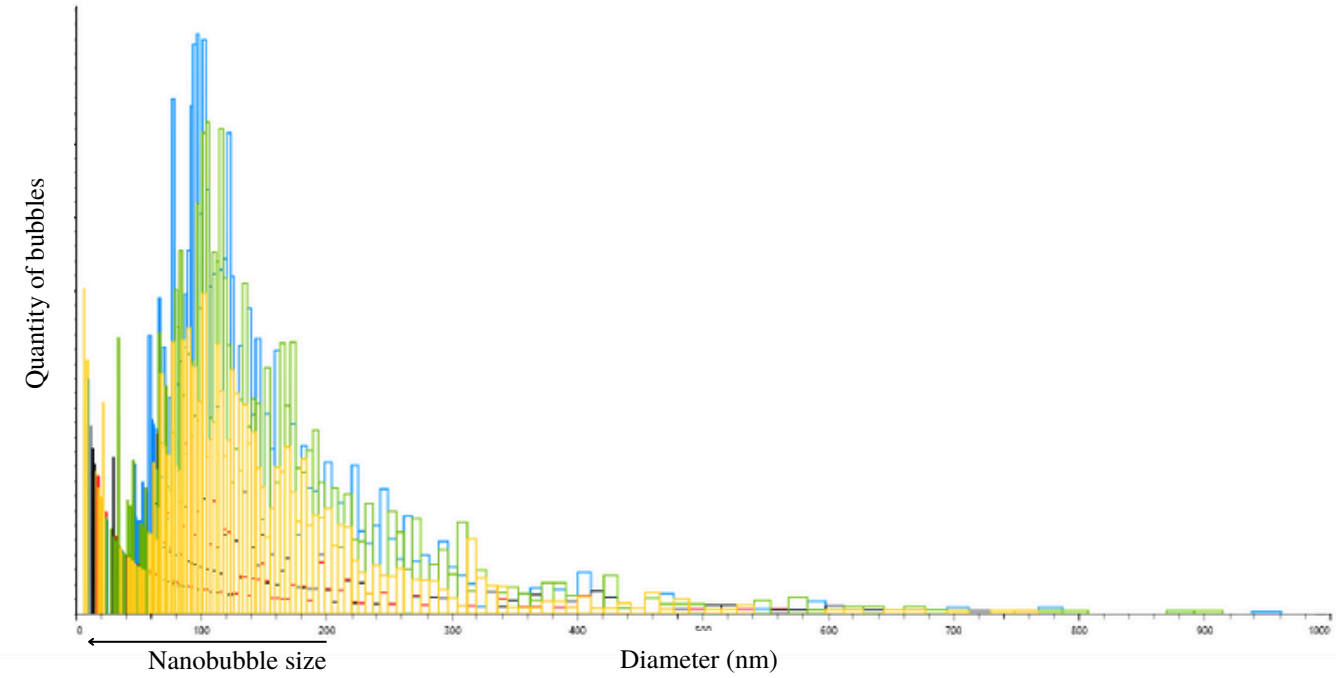
[1] Wang, Dujun, et al. Overexpression of OsMYB305 in Rice Enhances the Nitrogen Uptake Under Low-Nitrogen Condition. Frontiers in Plant Science, vol. 11, Apr. 2020, p. 369. PubMed Central, https://doi.org/10.3389/fpls.2020.00369.
[2] Suyantohadi, A., et al. Effect of High Concentrated Dissolved Oxygen on the Plant Growth in a Deep Hydroponic Culture under a Low Temperature. IFAC Proceedings Volumes, vol. 43, no. 26, Jan. 2010, pp. 251–55. ScienceDirect, https://doi.org/10.3182/20101206-3-JP-3009.00044.
[3] Ebina, K., Shi, K., Hirao, M., Hashimoto, J., Kawato, Y., Kaneshiro, S., Morimoto, T., Koizumi, K., & Yoshikawa, H. (2013). Oxygen and Air Nanobubble Water Solution Promote the Growth of Plants, Fishes, and Mice. PLOS ONE, 8, e65339. https://doi.org/10.1371/journal.pone.0065339
[4] Low Dissolved Oxygen in Water: Causes, Impact on Aquatic Life. https://www.pca.state.mn.us/sites/default/files/wq-iw3-24.pdf. Accessed 8 Jun. 2022.

Nanobubbles, however, are highly efficient and effective at increasing DO levels in water regardless of temperature. Indeed, lab and field trials have shown that water treated with Ion Solutions cold plasma technology quickly reaches 30 ppm of DO and 400% saturation.

According to Horiba's Particle Size Analysis using Nanoparticle Tracking Analysis (NTA) technology, Ion Solutions is capable of generating ultra-fine distribution of bubbles smaller than 130 nanometers in average size. Furthermore, the analysis determined that the water samples still contained millions of bubbles as small as 12nm after 48 hours. (For comparison, a human hair is 80,000-100,000nm wide.) Nanobubbles smaller than 1.2u can stay suspended in water in a latency state, acting as gas reservoirs and delivering their content to the environment on demand[1].

HORIBA Scientific

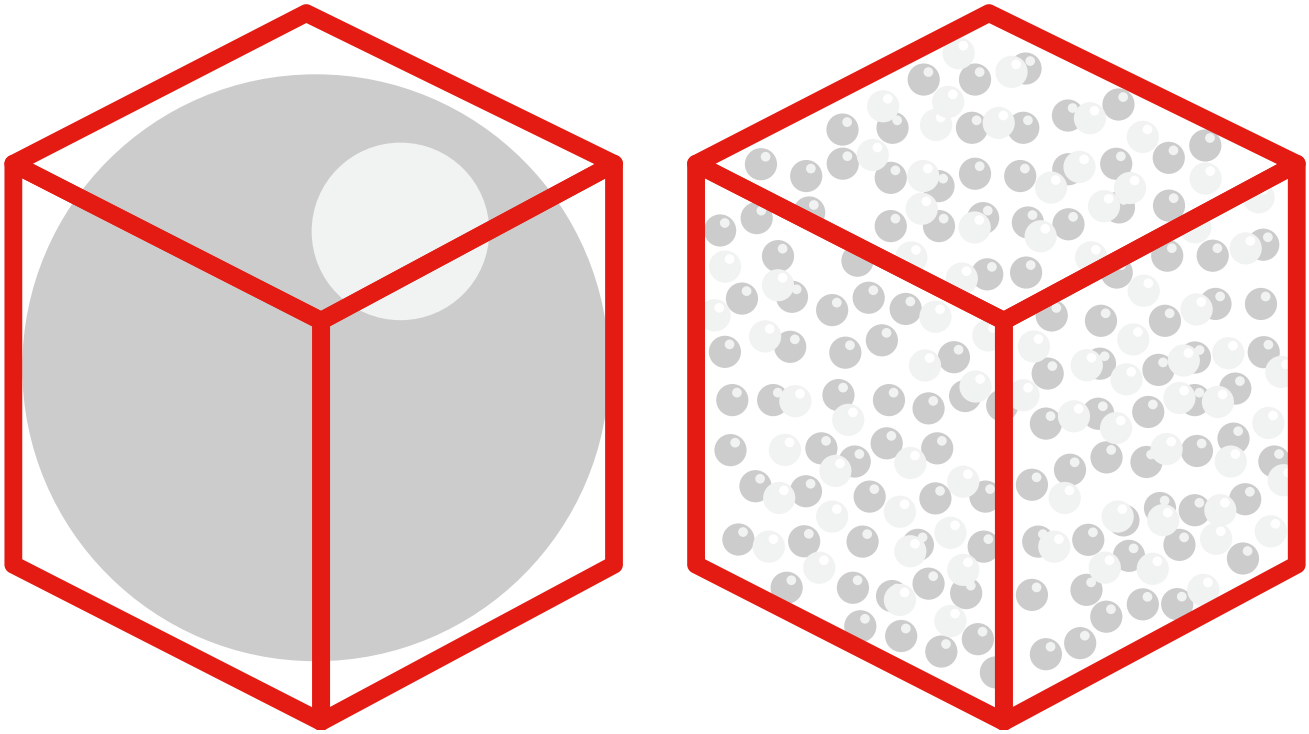
ViewSizer 3000 - Nanoparticle Size Analyzer



[1] Vehmas, Tapio, and Lasse Makkonen. Metastable Nanobubbles. ACS Omega, vol. 6, no. 12, Mar. 2021, pp. 8021–27. DOI.org (Crossref), https://doi.org/10.1021/acsomega.0c05384.

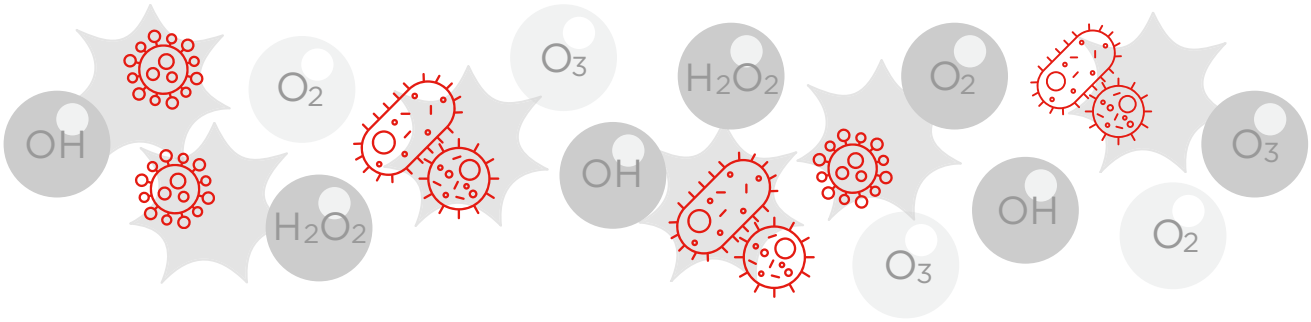
Nanobubbles are buoyantly neutral, meaning they don't readily rise to the surface of water. UFBs' trajectory within water is an illustration of Brownian motion—the principle of random and free travel of particles suspended in a medium. Nanobubbles can stay suspended for months, effectively oxygenating an entire water column over their long lifetimes[1].

Their small size also means a much larger surface area of oxygen for plant roots to access. One cubic mm volume of nanobubbles has 10,000 times greater surface area than 1 cubic mm of regular air bubbles, allowing for efficient aeration and increased mass transfer[2].



Ultra-fine bubbles (UFB) promote oxygenation efficiency because of their increased surface area.
One cubic mm volume of UFB has 10,000 greater surface area than 1 cubic mm of regular air bubbles.

[1] Vehmas, Tapio, and Lasse Makkonen. Metastable Nanobubbles. ACS Omega, vol. 6, no. 12, Mar. 2021, pp. 8021–27. PubMed, https://doi.org/10.1021/acsomega.0c05384.
[2] Md. Mahadi Rajib, P. F. (2017). Study on the number density of nanobubbles at varying concentration of ethanol in ethanol-water solution. AIP Conference Proceedings.



Reactive oxygen species (ROS) mitigate bacteria and pathogens

A 2016 study on cold plasma for enhancing the germination of radish seeds confirmed that treating the seeds with cold plasma could improve the radishes' growth rate by between 9% and 12% of the dry weight[1]. Similarly, experiments with cold plasma treatment on soybean seeds inoculated with Diaporthe/Phomopsis complex pathogens indicated that the resulting plants did not undergo oxidative stress due to the reduction in pathogens. Indeed, both the healthy control seeds and the infected experimental seeds showed no difference in vegetative growth[2].

[1] Matra, Khanit. Non-thermal Plasma for Germination Enhancement of Radish Seeds. Procedia Computer Science, vol. 86, Dec. 2016, p.132-135. https://www.researchgate.net/publication/303508667_Non-thermal_Plasma_for_Germination_Enhancement_of_Radish_Seeds

[2] Pérez-Pizá, Maria C., et al. Effects of non-thermal plasma technology on Diaporthe longicolla cultures and mechanisms involved. Pest Management Science, vol. 77, Apr. 2021, p. 2068-2077. doi: 10.1002/ps.6234. Epub 2021 Jan 5. DOI.org (Crossref), https://doi.org/10.1002/ps.6234

Sustainability Powered by Plasma-Activated Water

Cold plasma technology provides a number of ecological benefits—it's an environmental protection multitool that can help facilities reach their sustainability goals.
Compared to traditional water disinfection methods that may require high energy inputs, cold plasma treatment consumes relatively less energy. This reduces operating costs and promotes sustainable resource management.

In addition to its energy efficiency benefits, high levels of DO can lead to increased nutrient uptake without unnecessary over application of fertilizers. Studies have shown that treatment of rice seedlings and plants with oxygen-rich water upregulates plant nutrient absorption genes, resulting in the increased uptake of nutrients such as nitrogen and phosphorus through the roots. In a trial on rice plant cultivation, nanobubbles increased the yield in the experimental group by 8% compared with controls—and this increased yield was achieved with a 25% decrease in fertilizer usage in the experimental group[1].

The use of cold plasma technology to treat runoff water can lead to lower amounts of fertilizers entering waterways. This helps to decrease the potential for excessive nutrient buildup in waterways and the associated impacts on ecosystem health such as harmful algae blooms.

Water treated with cold plasma that exits a facility and flows into the water supply is of extremely high quality—potentially higher than it was when it entered the facility—due to its increased oxygen content and a lack of synthetic chemicals. Additionally, since Ion Solutions is able to maintain high Dissolved Oxygen levels even in high temperatures, it may lessen a facility's reliance on energy-intensive water coolers, which are often utilized in indoor agriculture.

[1] Wang, Ying, et al. Nanobubbles Promote Nutrient Utilization and Plant Growth in Rice by Upregulating Nutrient Uptake Genes and Stimulating Growth Hormone Production. Science of the Total Environment, vol. 800, Dec. 2021, p. 149627. DOI.org (Crossref), https://doi.org/10.1016/j.scitotenv.2021.149627.

The disinfecting and oxygenating properties of plasma-activated water reduce reliance on chemical interventions by cleaning irrigation lines and mitigating the potential for pathogen overgrowth. Consequently, water treated with cold plasma exits a facility and flows into the water supply is of extremely high quality - likely higher than it was when it entered the facility - due to its increased oxygen content and lack of synthetic chemicals. This also helps protect growers and consumers from chemical exposures.

Investment with Ingersoll Rand Ion Solutions

Cold plasma is a transformational technology for CEA and indoor farming, and Ingersoll Rand has taken this breakthrough innovation from the lab to the field with Ion Solutions, the world's first system to offer dual-mode disinfection and oxygenation using patented cold plasma technology.

This plug-and-play system has a small footprint, integrates seamlessly with existing cultivation facility operations and is IoT-enabled for maximum visibility and control. Ion Solutions' multitude of capabilities make it a smart, cost-effective investment that demonstrates positive ROI in a short period of time.

For both new and existing operations, this proven technology is here to expand cultivation potential and help businesses scale sustainably.

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