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Properties and Applications of Hydrogen Nanobubble Water: A Scientific Overview

Abstract

Hydrogen nanobubble water (HNBW) is an aqueous system in which molecular hydrogen (H2) gas is dispersed as stable, nanoscale gas cavities (typically 100–300 nm in diameter) within the bulk liquid. Unlike conventional hydrogen-saturated water, the nanobubble form is characterized by a high negative surface charge (zeta potential), extremely low buoyancy, near-zero rise velocity, and prolonged residence time, which together allow dissolved hydrogen concentrations and antioxidant activity to persist for weeks rather than minutes. This article reviews the physicochemical properties of hydrogen nanobubbles, the principal generation techniques (electrolysis, gas-shearing, ultrasonic cavitation, and pressurized dissolution with venturi/swirl-flow mixing), and the analytical methods used to characterize them (dynamic light scattering, nanoparticle tracking analysis, and dissolved-hydrogen electrodes). The reported and proposed applications of HNBW are then surveyed across four domains: biomedical and health-related use as a selective antioxidant and anti-inflammatory agent; agricultural use in irrigation, seed priming, and hydroponics; food and beverage processing; and environmental and industrial water treatment, including enhanced flotation and remediation. The article concludes by summarizing current evidence gaps, including the need for standardized bubble-size reporting, longer-term stability data, and rigorously controlled clinical trials, and by outlining priorities for future research.

Keywords

hydrogen nanobubbles; molecular hydrogen water; nanobubble stability; zeta potential; antioxidant water; nanobubble generation; water treatment; agricultural water technology

1. Introduction

Molecular hydrogen (H2) has attracted growing scientific interest since early reports that it can act as a selective antioxidant, reacting preferentially with highly reactive oxygen species such as the hydroxyl radical while leaving physiologically important reactive oxygen species largely unaffected. Because H2 has limited solubility in water under ambient conditions (approximately 1.6 ppm at atmospheric pressure and room temperature) and diffuses out of solution rapidly, delivering and retaining meaningful concentrations of dissolved hydrogen has been a persistent technical challenge.

Nanobubble technology offers a potential solution to this problem. A nanobubble is a gas-filled cavity with a diameter below one micrometer, small enough that Brownian motion dominates over buoyant rise, allowing the bubbles to remain suspended in liquid for days, weeks, or, in some reports, months. When the internal gas is hydrogen, the resulting dispersion is termed hydrogen nanobubble water (HNBW). In principle, HNBW combines the chemical reactivity of molecular hydrogen with the physical stability of the nanobubble carrier, yielding a water matrix in which dissolved and bubble-entrained hydrogen persist far longer than in simple hydrogen-saturated water produced by electrolysis or gas sparging alone.

This article summarizes the current scientific understanding of hydrogen nanobubble water: how it is generated, what physical and chemical properties distinguish it from ordinary hydrogen-rich water, and the range of applications that have been proposed or investigated in agriculture, food science, environmental engineering, and human health. Where the evidence base remains preliminary, this is noted explicitly, since much of the applied literature on HNBW is still emerging and requires confirmation through larger, better-controlled studies.

2. Physicochemical Properties of Hydrogen Nanobubbles

2.1 Size, Surface Charge, and Longevity

Hydrogen nanobubbles typically range from approximately 70 to 300 nm in diameter, as measured by dynamic light scattering (DLS) and nanoparticle tracking analysis (NTA). Their surfaces carry a net negative charge, generally reported as a zeta potential between −20 and −40 mV, arising from preferential adsorption of hydroxide ions and other anionic species at the gas–liquid interface. This surface charge produces electrostatic repulsion between adjacent bubbles, which limits coalescence and is considered a primary mechanism behind their unusually long lifetime compared with microbubbles or macrobubbles.

A second contributing factor is the negligible buoyant force acting on particles of this size: Stokes' law predicts a rise velocity that scales with the square of bubble radius, so nanobubbles rise so slowly that Brownian diffusion and convective mixing dominate their transport. The combination of surface charge stabilization and minimal buoyancy allows HNBW to maintain measurable dissolved hydrogen concentrations, commonly in the range of 0.5–1.6 ppm depending on generation method and storage conditions, for periods reported from several days up to multiple weeks in sealed containers, in contrast to simple hydrogen-saturated water, which typically loses the majority of its dissolved hydrogen within hours of exposure to air.

2.2 Internal Gas Pressure and Interfacial Behavior

The Young–Laplace relationship predicts that the internal pressure of a spherical bubble increases as its radius decreases, which would be expected to drive rapid gas dissolution and bubble collapse for structures at the nanoscale. The persistence of nanobubbles well beyond the timescale predicted by simple diffusion models remains an active area of physical chemistry research; proposed explanations include the stabilizing effect of the charged interfacial layer, local supersaturation of gas in the surrounding liquid shell, and reduced gas permeability at the bubble interface. Regardless of the precise mechanism, the empirical observation across multiple independent studies is that nanobubble populations decay far more slowly than classical bubble-dissolution theory would predict.

2.3 Generation Methods

Several techniques are used to produce hydrogen nanobubble water, each with different trade-offs in bubble density, size distribution, and scalability:

- Electrolysis-based generation: water is electrolyzed to liberate H2 at the cathode; the evolved gas is captured and mechanically dispersed into fine bubbles, often combined with a downstream nanobubble generator.
- Pressurized dissolution (gas-to-liquid) systems: hydrogen gas is dissolved into water under elevated pressure and then released through a venturi, swirl-flow, or micro-orifice nozzle, causing sudden pressure reduction that shears the gas into nanobubbles.
- Ultrasonic cavitation: high-frequency acoustic energy is applied to hydrogen-saturated water, generating and collapsing microbubbles whose fragments stabilize as nanobubbles.
- Ceramic or porous-membrane diffusion: hydrogen gas is forced through a microporous membrane submerged in water, producing a fine bubble stream that is further reduced in size by shear forces.

Generation conditions (pressure, flow rate, gas purity, water temperature, and dissolved-ion content) strongly influence the resulting bubble size distribution and zeta potential, which is why comparability across studies using different equipment remains limited.

2.4 Characterization Methods

Rigorous characterization of HNBW typically combines several complementary techniques: dynamic light scattering and nanoparticle tracking analysis for bubble size distribution and concentration; laser Doppler electrophoresis for zeta potential; dissolved-hydrogen electrodes or gas chromatography for quantifying dissolved H2 concentration; and, in some studies, cryogenic transmission electron microscopy or resonant mass measurement for direct visualization. Because reported bubble concentrations and sizes vary considerably with measurement technique and instrument calibration, comparison across the published literature should be made cautiously.

3. Applications

3.1 Biomedical and Health-Related Applications

The largest body of applied research on hydrogen-rich water, including nanobubble formulations, concerns its potential role as a selective antioxidant. In vitro and animal studies suggest that molecular hydrogen can reduce oxidative stress markers and mitigate inflammation in models of ischemia-reperfusion injury, metabolic disturbance, and exercise-induced oxidative stress. HNBW has been proposed as a delivery vehicle for oral or topical hydrogen administration because its extended hydrogen retention may allow more consistent dosing than freshly prepared hydrogen water. However, most human trials to date involve small sample sizes, short durations, and heterogeneous outcome measures, and results for benefits such as improved exercise recovery, skin hydration, or metabolic markers remain preliminary. Larger randomized, placebo-controlled trials with standardized HNBW formulations are needed before firm clinical conclusions can be drawn, and HNBW should not be regarded as a substitute for established medical treatment.

3.2 Agricultural and Horticultural Applications

In plant science, hydrogen-rich irrigation water and seed-priming solutions have been investigated for effects on germination rate, root development, and tolerance to abiotic stress such as salinity and drought. Proposed mechanisms include hydrogen's scavenging of excess reactive oxygen species in plant tissue under stress conditions and secondary effects on nitric oxide signaling pathways involved in root growth. Nanobubble delivery is of particular interest in hydroponic and greenhouse systems, where the extended persistence of dissolved hydrogen and elevated dissolved-oxygen co-benefits (many nanobubble generators can also be configured for oxygen) may improve nutrient uptake efficiency and root-zone aeration relative to conventional aeration methods. As with the biomedical literature, most agricultural findings derive from controlled greenhouse or laboratory trials, and field-scale validation across crop species and soil types remains limited.

3.3 Food and Beverage Applications

In food processing, nanobubble water has been explored for applications including produce washing, where the fine bubble structure and associated micro-scale turbulence are reported to improve removal of surface residues and microbial load compared with conventional washing, and for extending the shelf life of fresh produce and seafood through modest antimicrobial and antioxidative effects. Hydrogen-infused beverages, marketed as hydrogen water, represent a consumer product category in which nanobubble technology is used specifically to slow the loss of dissolved hydrogen during bottling, storage, and shelf display, addressing a key limitation of earlier hydrogen-water products that lost most of their hydrogen content shortly after packaging.

3.4 Environmental and Industrial Water Treatment

Nanobubble technology more broadly (not limited to hydrogen) is established in water and wastewater treatment for applications such as dissolved air flotation, aeration of aquaculture ponds, and enhanced mass transfer in oxidation processes, owing to the high surface-area-to-volume ratio and long residence time of nanobubbles. Hydrogen-specific nanobubble applications in this domain are comparatively less developed but have been proposed for reductive remediation processes, where dissolved hydrogen can act as an electron donor to support microbial or catalytic reduction of certain contaminants, including chlorinated solvents and select oxidized metal species, in groundwater and industrial effluent treatment systems. These applications remain largely at the pilot or laboratory-demonstration stage.

4. Discussion and Evidence Gaps

Across all application areas, three methodological limitations recur in the current literature. First, bubble size, concentration, and zeta potential are reported using inconsistent instrumentation and units, which complicates direct comparison between studies and commercial products. Second, long-term stability data beyond several weeks are scarce, and the influence of storage temperature, container material, and agitation on hydrogen retention is not yet systematically mapped. Third, many applied studies, particularly in the health and agriculture domains, are conducted at small scale or without adequate controls, so mechanistic claims linking hydrogen nanobubbles to specific biological or agronomic outcomes should be treated as hypotheses requiring further confirmation rather than established fact.

5. Conclusion

Hydrogen nanobubble water is a physically distinct form of hydrogen-enriched water in which nanoscale, negatively charged, low-buoyancy gas cavities substantially extend the retention of dissolved molecular hydrogen relative to conventional hydrogen-saturated water. This property has motivated exploratory research into applications spanning selective antioxidant therapy, plant stress mitigation, food and beverage processing, and environmental remediation. While the underlying physical chemistry of nanobubble stability is increasingly well characterized, the applied evidence base—particularly for health-related claims—remains at an early stage and is constrained by inconsistent characterization methods and a scarcity of large, well-controlled studies. Future work should prioritize standardized reporting of bubble size and dissolved-hydrogen concentration, longer-duration stability studies under realistic storage conditions, and rigorously designed trials to establish which proposed benefits of hydrogen nanobubble water are reproducible and clinically or agronomically meaningful.