

NANOBUBBLE TECHNOLOGY FOR SOIL REMEDIATION: CURRENT PROGRESS, MECHANISTIC INSIGHTS, CHALLENGES, AND FUTURE PROSPECTS

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Abstract

Nanobubble technology can be a game-changer for the soil remediation sector, which faces significant challenges in combating soil contamination to ensure food security and overall ecosystem health. Nanobubbles are smaller bubbles with a diameter less than one micrometer that have extraordinary properties such as very large specific surface area, high stability, and strong negative surface charge and capacity to produce reactive oxygen species. The present review gives a comprehensive synthesis of nanobubble application technology in soil remediation including understanding the mechanism and their applications in soil remediation of both organic contaminant and inorganic contaminant. Mechanisms include improving gas transfer, oxygenating the soil, contaminant release and mobility, production of reactive oxygen species, soil-microbe-plant interaction with increased soil biodegradation. Enhancements in plant growth of 10-50% and contaminant removal efficiencies of up to 75-98% have been seen for petroleum hydrocarbons, pesticides, heavy metals and emerging persistent contaminants. Synergistic hybrid systems come with integration to bioremediation, phytoremediation, biochar and advanced oxidation. Laboratory to field translation and protocols standardization, ecotoxicological evaluation and economic feasibility are key challenges. Future directions include precision remediation via smart monitoring and adaptive management using AI. The review concludes that nanobubble technology holds

1. INTRODUCTION

Contamination of soils is a critical issue of the 21st century, which poses a threat to food security, ecosystem sustainability and human health globally. Soil contamination has undergone extensive contamination by organic pollutants, heavy metals and emerging persistent pollutants, due to industrial activities, agricultural intensification, mining activities and improper waste disposal. Soil contamination poses long-term environmental risks, with petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), pesticides, chlorinated compounds and toxic metals (lead, cadmium, chromium, mercury and arsenic) being among the contaminants. Economic costs of soil clean-up are significant and amount to several billions of dollars in the world annually on average, and ecological and health costs are not measurable. Climate change aggravates these problems through changes in the mobilization of contaminants, soil degradation, and further stress on arable land resources on which an increasing global population relies[1]. There are many technical and economic challenges inherent in traditional methods of soil remediation, such as excavation and disposal, soil washing, thermal desorption, pump-and-treat systems, and chemical oxidation. These processes will frequently demand high amounts of energy and will create new waste streams and can, to a certain degree, change the physical and chemical properties of the soil, thus affecting soil ecological functions and farm productivity. Bioremediation and phytoremediation have more sustainable alternatives but they are limited by degradation kinetic, availability of contaminant and by the presence of inhibitory concentrations of toxic compounds and/or deficient amounts of nutrients (such as oxygen, nitrogen and phosphorous) in the soil. Inherent mass transfer constraints in the porous soil matrix inhibit the efficiency of gas-based remediation strategies because traditional aeration cannot be relied upon to distribute oxygen uniformly, which leaves some anaerobic areas where gas-based remediation

cannot be expected to degrade organic contaminants aerobically. This quest for an innovative technology that can remove these mass transfer constraints without harming the soil health and facilitate sustainable remediation efforts has made nanobubble technology a growing area of research[2].

The nanobubble is a spherical bubble whose size is smaller than 1 micrometer and has extraordinary physicochemical properties that differentiate it from previously known macroscopic bubbles. The remarkable stability in the presence of water, strong negative surface charge, capacity to generate reactive oxygen species and exceptionally high specific surface area have made them the interest of research in many applications including environmental remediation, agriculture, water treatment and biomedical applications. In soil remediation applications, nanobubbles provide a paradigm breakthrough by providing a means to circumvent the limitations of conventional mass transfer mechanisms, to deliver deep oxygen penetration into soil matrices, to support contaminant desorption, to stimulate microbial activity and to sustain oxygenation of the rhizosphere. Improvements in plant growth have been reported to be in the range of 10 to 50 percent, and contaminant removal efficiencies as high as 75 to 98 percent for different pollutants show the potential for transformational change with this technology. Nanobubbles' ability to simultaneously improve plant growth and soil remediation puts it at the heart of sustainable soil management and climate-resilient agriculture[3]. Although extensive research about the use of nanobubbles in soil systems has been conducted, there is still a need for a general review on the mechanistic knowledge, technological development, and practical implementation of nanobubble usage in soil systems. This review consists of a systematic compilation and critical analysis of the nanobubble technology for soil remediation based on existing knowledge obtained from laboratory investigations, greenhouse soil studies and the few applications at

the field scale that have emerged. The topics covered here span from the basic physical and chemical properties of nanobubbles, their synthesis and characterization, mechanism of remediation activity, interaction with soil-microbe-plant systems, nanobubble-assisted remediation of organic and inorganic contaminants, hybrid remediation strategies, to scalability issues. The novelty of this review is mainly focused on summarizing the nanobubble behavior in the porous soil media, understanding the nanobubble interfacial mechanism, reviewing the prospect of rhizosphere-microbiome interaction, and also highlighting the critical issues of environmental risks and knowledge gaps that need to be addressed for successful technology deployment[4].

2. Fundamentals of Nanobubble Technology

2.1 Definition and Classification of Nanobubbles

Conventionally, nanobubbles are defined as gas-filled bubbles with diameters less than 1 μm (the lower end of the size range of micro-nano bubbles). Micro-nano bubbles cover the whole range of bubbles, from larger ones (10mm to 100 μ) known as macrobubbles, to the smaller ones (100 μ to 10 μ) referred to as microbubbles, submicron bubbles (10 μ to 1 μ), and nanobubbles (less than 1 μ). This size categorisation is fundamental because at the nanometer scale, the unique physicochemical properties of nanobubbles become more prominent as the surface area-to-volume ratio scales up fast, and then interfacial phenomena govern the behavior. Nanobubbles can be present in two main forms: bulk nanobubbles, which are nanobubbles present in the liquid phase, and interfacial nanobubbles, which are nanobubbles that adhere to a solid surface[5]. Bulk nanobubbles are obtained by different cavitation and dissolution techniques, and remain free in solution, while interfacial nanobubbles are created by heterogeneous nucleation at solid-liquid interfaces. Their difference is essential to understanding their role in remediation mechanisms in porous soil systems where both bubbles suspended in the soil water (soil-water interface) and bubbles attached to the soil-water interface (soil particle surface) are present[6].

2.2 Physicochemical Properties and Stability

One of the most remarkable and technologically significant properties of nanobubbles is their extraordinary stability against dissolution, even though this property is contrary to classical thermodynamic laws. The collapse of nanometer-sized bubbles is predicted by classical theory to happen within microseconds because of the high pressure inside the bubble; yet, nanobubbles have been observed to exist over days, weeks, or months in an aqueous environment. The mechanisms responsible for this anomalous stability are the formation of a high density gas layer at the bubble interface, the surface charges which generate repulsive forces able to compensate the dissolving pressure, and the shielding effect of gas molecules that are dissolved and surround the bubble surface[7]. Nanobubbles have a high density surface charge layer with a strong interfacial electric field due to the preferential adsorption of anions, such as hydroxide ions on the gas-liquid interface of the nanobubbles in aqueous solutions. The results of zeta potential measurement also find that the surfaces of the nanobubbles are always negative charged, indicating uniform electrostatic property of nanobubbles under various pH values. As the particles get smaller, from micro to nano scale, the number of nanobubbles becomes higher for the same gas volume fraction, and the specific surface area by orders of magnitude. These properties allow nanobubbles to be well-distributed in the liquid phase, create large reactive surfaces and enable long-term delivery of gas in soil systems[8].

2.3 Nanobubble Generation Technologies

Nanobubbles can be produced by different physical, chemical, and physicochemical processes, each with its own unique strengths and drawbacks in different applications. Currently existing cavitation based approaches such as hydrodynamic cavitation, acoustic cavitation and pressure decompression are the most used methods for nanobubble generation. Hydrodynamic Cavitation is based on compressing liquid within a hydrodynamic system creating a pressure drop that promotes the nucleation of dissolved gas into bubbles. Acoustic cavitation makes use of

ultrasound energy to cause the areas of high pressure and low pressure to generate and collapse bubbles. Pressure Compression Methods are those that involve supersaturating or bubble nucleating the water in the presence of gas at high pressures[9]. Electrolysis is advantageous for small volume preparation and research due to higher gas purity, smaller particle size and good control of the quality of bubbles. Nanobubbles are generated via the well-controlled desorption of gas from the water during solvent exchange, which involves the mixing of water saturated with gas with water with lower gas solubility. Different production methods are known to have a significant impact on nanobubble properties such as size distribution, concentration, surface charge and stability, which are significant for their soil remediation performance[10].

2.4 Characterization and Measurement Approaches

The size distribution, concentration, surface charge, and stability of nanobubbles, for instance, must be correctly characterized, to understand their behavior in the soil system and to optimize their use for remediation. In particular, the Nanoparticle Tracking Analysis (NTA) method has become one of the standard methods of nanobubble characterization because it allows a precise measurement of the size and number of particles by analysing their Brownian movement and light scattering. This technique yields size distribution profiles and particle concentrations which show that nanobubble populations produced by industrial methods are poly-disperse[11]. Dynamic Light Scattering complementary information on hydrodynamic diameter and size distribution, Zeta Potential complementary information on surface charge and colloidal stability. The morphology of nanobubbles can be directly seen by electron microscopy such as Cryo-Transmission Electron Microscopy and Scanning Electron Microscopy, and must be prepared carefully to prevent the generation of artefacts. The Tyndall effect experiment has been proven to be a simple and effective way to verify that capacity of nanobubble generation in a soil system, since light scattering by

nanobubbles is proof of their existence. In recent years, there have been developments of microfluidic platforms with Nanoparticle Tracking Analysis (NTA) for in-situ characterization of nanobubble generation at soil interfaces, which allows quantitative analysis of the influence of soil properties on bubble formation[8].

2.5 Behavior of Nanobubbles in Porous Soil Systems

The flow and trapping of nanobubbles in fully saturated porous rocks is influenced by complex interplay between bubble properties, porous media properties and hydrodynamic conditions. Grain size and shape significantly affects nanobubble retention as smaller sizes increases the tortuous flow path and affords more opportunities for attachment. Pore size distribution and the presence of colloidal fines significantly influence the transport behaviour, while both smaller pores and higher fines content favour retention of bubbles by physical straining and by surface interaction. Theoretical study shows that when the nucleation Gibbs free energy is critical, aggregation of the dissolved gas molecules in soil water takes place at soil surfaces as a result of collisions[12]. Soil interfaces generate different amounts of nanobubbles, depending on soil hydrophobicity and the supersaturation level of the soil gas, with quartz leading with 16.58×10^7 particles per milliliter, close to the nanobubble production of industrial processes. This is the first study to apply regression modeling to this phenomenon to establish quantitative relationships between soil hydrophobicity and nanobubble concentrations and ensure that the models were accurate in prediction using actual soil samples. Overall, interfacial nanobubbles attached to porous substrate like biochar and clay serve as sites of slow release oxygen, and they targeted and sustained hypoxic soil microsites. Knowledge of these transport and retention mechanisms is important in considering effective field-scale remediation applications[13].

3. Mechanistic Basis of Nanobubble-Mediated Soil Remediation

3.1 Enhanced Gas Transfer and Soil Oxygenation

Nanobubble's main mechanism of action for use in soil remediation is that they result in a very high efficiency in gas transfer and continuous oxygenation of the soil. The drawbacks of conventional aeration methods are high rise velocity of bubbles, poor gas dissolving efficiency and low bubble penetration depth in porous media. The extremely low rise velocity and high internal pressures of the nanobubbles increase the time that they stay in the liquid phase, and allow for an efficient dissolution of oxygen and penetration into the soil profiles. Nanobubbles' high specific surface area allows them to exchange rapidly with the surrounding solution, further, keeping the level of dissolved oxygen high even in oxygen demanding soil environments[3], [14]. In oxygen-starved rhizospheres, application of nanobubbles overcomes the constraints on root respiration and increases the uptake of nutrients in the rhizosphere, which in turn leads to the growth enhancement of plants and activation of aerobic microorganisms in the soil. The continuous oxygenation feature of nanobubbles is especially useful for the hydrocarbon contaminated soils where aerobic degradation is the major degradation route. Use of oxygen nanobubbles in irrigation water can effectively raise the dissolved oxygen content, improve enzymatic degradation and aerobic respiration processes to promote the biodegradation of complex organics. The ability to maintain higher oxygen levels in root zone soils for longer periods of time is what makes nanobubble technology different from the conventional methods of aeration, which also allows for the more efficient remediation of oxygen deficient contaminated soils[4], [14], [15].

3.2 Contaminant Desorption and Mobilization

Nanobubbles can release and mobilize soil-bound contaminants, and do so in a number of synergistic ways, overcoming one of the key challenges of current remediation technologies. Nanobubbles have a high surface charge density,

which is strong electrostatic interactions with the soil particles and contaminants, disrupts the binding of contaminants and soil particles and is strong in release of contaminants. Nanobubbles penetrate into the soil micropores and hydrophobic domains, helping to displace surface bound contaminants and make them more available for further degradation or removal[16]. Nanobubbles offer gas-liquid interfaces which act as adsorption sites for amphiphilic contaminants, thereby offering a molecular foundation for enrichment and removal at the interface. The perfluorocarbon chain of per- and polyfluoroalkyl substances (PFAS) is inserted in the gas phase of nanobubbles, and the anionic head groups are arranged in an ordered way at the nanobubble-water interface. This mechanism works especially well for organic contaminants which prefer to partition to interfaces that remain in the aqueous phase. Such contaminant mobilization via nanobubble systems improves bioavailability, which results in more effective biodegradation, chemical oxidation and/or physical extraction, depending on the remediation approach. Contaminant desorption is also caused by change in the soil physicochemical properties upon nanobubble treatment such as soil structure, redox potential and surface chemistry[2], [17].

3.3 Reactive Oxygen Species Generation

Nanobubbles' generation of reactive oxygen species, especially hydroxyl radicals, provides a different way of degrading contaminants than a biological way. As the nanobubbles collapse or fluctuate with pressure, highly reactive species such as hydroxyl radicals, superoxide radicals, and singlet oxygen, are formed in the extreme environment of the gas-liquid interface. These species have a high oxidation potential and have the ability to directly oxidize organic contaminant by oxidative cleavage of chemical bonds. With the addition of electrolytes and catalysts, the electrolyzed catalytic nanobubble water systems exhibit an improved production of radicals, which gives the water an added oxidative power from the sulfate radicals[18]. The standard reduction potential of reactive species allows oxidation of a diversity of organic contaminants, even those

compounds that are not amenable to biological degradation. Reactive oxygen species are produced at soil interfaces that can contribute to the transformation and mineralization of contaminants in addition to biological degradation processes. Electrolytes like alkali electrolyte sodium chloride or potassium sulfate increase the efficiency of radical production due to the increase of electrical conductivity and to increase the hydrodynamic cavitation effect. Porous media dispersion of nanobubbles ensures distribution of the generation of reactive species in space, to provide oxidative treatment throughout the contaminated soil profile[19].

3.4 Soil-Nanobubble-Contaminant Interactions

The soil constituents, nanobubbles and contaminants interact in a complex manner, and their interaction mechanisms need to be understood to design application for predictable remediation efficiency. The hydrophilicity of the soil constituents like goethite, humic acid, graphite, molybdenite, pyrite and quartz, varies to differing extents, and has a fundamental effect on the heterogeneous nucleation rate of nanobubbles at solid surfaces. Both the ability of soil interfaces to produce nanobubbles and the soil hydrophobicity have been correlated quantitatively and have been modelled empirically with mathematical relationships. Concentrations of nanobubbles showed positive correlations with both soil hydrophobicity and levels of gas supersaturation, reflecting that the formation of bubbles is mostly driven by the surface chemistry[10]. The presence of charged nanobubbles produces a microenvironment at the soil-water interface which can alter contaminant partitioning, surface adsorption, and reaction kinetics. Nanobubble generation can cause large variations in the local pH which can have significant effects on the speciation of the contaminants and the soil surface charge, as was demonstrated in rainwater, where the pH rose from 5.28 to 7.76 during nanobubble generation. It is important to understand these interaction mechanisms for proper choice of the type of gases, bubble size and application conditions for

particular types of contaminated soil and contaminant profile[2], [10].

3.5 Modification of Soil Physicochemical Properties

In addition to direct nanobubble-contaminant interactions, treatment of nanobubbles causes changes to the soil's general physicochemical properties, which affect the fate, activity of microorganisms, and function of the ecosystem. Improvement of soil structure is through the formation of stable aggregates, porosity, water infiltration and water retention. Nanobubbles in soil water alter surface tension and wetting properties which impact water distribution and contaminant mobilization. Generation of nanobubble effects on electrical conductivity and changes in pH can affect the speciation, solubility and bioavailability of the contaminants[18]. Redox potential changes that occur as a result of ongoing oxygenation can result in positive circumstances for aerobic biodegradation and may change the speciation of metals, affecting mobility and toxicity. Therefore, the nutrient availability is increased by better oxygen transport, stimulating nutrient cycling microorganisms, and altering sorption-desorption equilibria. It impacts soil organic matter dynamics by oxidative transformation and via altered microbial processing. All of these physicochemical changes combine to produce a more conducive environment for contaminant degradation, root growth and soil ecosystem function. The ability to modify a host of these soil properties shows that nanobubble technology has the potential to work in suboptimal environments by reducing the effect of toxicity, salinity, alkalinity and root-zone hypoxia[20].

4. Nanobubble-Microbe-Plant Interactions in Soil Remediation

4.1 Stimulation of Indigenous Soil Microorganisms

Soil microbes in contaminated soils are very sensitive to the nanobubble application, which has significant stimulatory effects on these natural communities, unlocking pathways of biological degradation in addition to the pathways of

physicochemical degradation of contaminants. Better oxygen transfer by nanobubbles promotes the transition from anaerobic to aerobic conditions in waterlogged or compacted soils, thus allowing growth of aerobic microorganisms which usually are the most efficient degraders of organic contaminants. Adjusting rootzone O₂ levels to alleviate O₂ limitation provides increased metabolic activity and growth of beneficial aerobic microbiological community and oxygen nanobubbles are delivered via irrigation water[21]. Enzymes produced by the microbes, respiration and biomass are higher as more oxygen is available, which further increases the degradation capacity, creating a positive feedback loop. Moderate levels of ROS production may be used by microorganisms as signaling molecules for initiating stress responses and adaptive metabolic pathways, and thus increase their capacity to degrade xenobiotics. These changes in soil physical and chemical properties, such as increased porosity, nutrient availability and surface chemistry, promote enhanced soil microbial colonization and activity. In situ microorganisms that are already present in the soil and optimised for the type of soil and type and concentration of contamination are preferred, thus decreasing the need for bioaugmentation and improving the sustainability of the remediation strategy[22].

4.2 Enhancement of Microbial Biodegradation

The multiple complement pathways of nanobubbles on assisting in microbial biodegradation effectively contribute towards faster rates of mineralization of contaminants. The desorption and mobilization of contaminants result in higher bioavailability of contaminants, which enhances the accessibility of substrates for microorganisms which would be sequestered in soil micropores or tightly sorbed on soil organic matter. The presence of an ongoing oxygen supply facilitates the utilization of oxidative metabolic pathways for the production of energy to support growth and for co-metabolic degradation of recalcitrant compounds. The nanobubbles of oxygen at the porous material–water interface act as local oxygen reservoirs, providing aerobic microenvironment within anaerobic soil

aggregates; hence, aerobic degradation can proceed in the presence of oxygen nanobubbles in the mixed media – soil[10]. Nanobubble-treated soils have been seen to stimulate the growth of specific functional groups of microbes that are necessary for key degradation processes, which suggests a selective enrichment or physiology enhancement of microbes with these metabolic traits by applying bubbles. Nutrient cycling enhancement to increase oxygen availability and microbial activity helps increase the availability of nitrogen, phosphorus, and other nutrients critical to the biodegradation processes. The combination of nanobubble technology with the proven bioremediation techniques of biostimulation and bioaugmentation leads to synergistic effects which greatly exceed either technology alone[23].

4.3 Microbial Community and Functional Shifts

Microbiological community composition and function were significantly altered with nanobubble treatment with impacts on contaminant degradation and other soil processes. Selective stimulation of aerobic microorganisms by the exclusion of anaerobic microorganisms changes the microbial community to higher functional diversity of oxidative transformations. Oxygen responsive genes and pathways are activated which leads to higher expression of oxygenases, dehydrogenases and other enzymes which degrade the contaminant. The community changes to higher proportions of more metabolically versatile, environmentally stress resistant population, which results in more stable degradation capacity under variable conditions. Redundancy among microbes would allow degradation functions to be provided even through the loss of individual populations. Nanobubbles change the soil's chemical and physical properties, allowing for the development of certain functional groups such as hydrocarbon degraders, metal oxidizers, and nutrient cycling organisms[24]. The microbial community changes are not immediately reversed upon cessation of nanobubble treatment, thus allowing for ongoing remediation effect due to nanobubble influences on the soil properties and population of microorganisms. Knowing these community

dynamics will help predict long term remediation performance and help optimize application strategies[25].

4.4 Nanobubbles and Rhizosphere Microbiomes

The rhizosphere is the area surrounding the plant roots which forms a "hotspot" of microbial activity and contaminant degradation and in which nanobubble application can be used to boost these processes greatly. Nanobubbles introduced into the rhizosphere via irrigation promote the growth of roots and root exudates, which favours the production of carbon substrates for microbes metabolism and co-metabolic degradation. Rhizosphere oxygenation enhances aerobic degradation near the roots as the release of oxygen from the roots also increases. The root associated microbial community is stimulated by improved oxygen availability, enhanced nutrient cycling, increased root exudate production, which in turn enhances degradation, starting a cycle which accelerates further degradation. The results of growth and physiological parameters of halophytic plant *Tamarix smyrnensis* showed that the highest biochar application rate (HBC) significantly increased the TCC in the treatment using nanobubble irrigation alone (97.6 percent) and in the combined treatment (136 percent). Root zone community (rhizosphere microbiome), including plant growth promoting rhizobacteria, strengthened which promotes plant growth and degradation of contaminants. The combination of nanobubbles, plant roots, and rhizosphere microorganisms is a synergic system capable for sustainable soil remediation and restoration[26].

4.5 Integration with Phytoremediation and Bioremediation

The use of nanobubble technology in conjunction with phytoremediation and bioremediation results in hybrid strategies that help to maximize the strengths of each while minimizing potential weaknesses and limitations. Nanobubble-induced improvements in plant health, root growth and contaminant bioavailability enhance phytoremediation (plant uptake, binding, and breakdown of contaminants). Nanobubble oxygenation leads to a higher root biomass and

activity, which will enlarge the soil volume that can be influenced by phytoremediation and accelerate the rate of contaminant uptake or degradation. The availability of oxygen, desorption of contaminants, and cycling of nutrients can be enhanced with nanobubbles, which helps bioremediation by use of bioaugmentation (introducing certain degrader strains) or biostimulation (stimulating the existing strains in situ)[18]. An especially promising hybrid approach is the combination of nanobubbles with biochar which is loaded with nanobubbles and therefore capable of continuing to oxygenate while it can still bind contaminants. The incorporation with advanced oxidation systems, such as ozonation and photocatalytic oxidation, enables systems to treat the most recalcitrant contaminants in combined oxidative and biological processes. The adaptability of nanobubble technology allows hybrid approaches tailored to contaminant loadings, soil characteristics, and objectives for remediation, thereby offering a flexible platform to achieve sustainable soil remediation[10].

5. Applications for Organic Contaminant Remediation

5.1 Petroleum Hydrocarbons and PAHs

Petroleum hydrocarbons and polycyclic aromatic hydrocarbons are among the most ubiquitous and persistent organic contaminants found in soil systems and the need for effective remediation strategies which can be applied to the complex mixture composition and recalcitrant nature of these contaminants cannot be overlooked. Nanobubble technology has been proved to be very effective in the physical and oxidative remediation of soils contaminated with diesel oil. An innovative electrolyzed catalytic system developed for the generation of the nanobubble system remediated the contaminated soil that contained diesel-oil efficiently, and the radical production efficiency was enhanced by adding the electrolytes and catalysts[27]. Micro-nano bubble oxidation process can be combined with the treatment of surfactants and additives, significantly promote the workability of the additives, the process is short, low cost, high efficiency and is a real effective method for

efficient treatment of petroleum contamination. A nanobubble provides an extended source of oxygen to drive aerobic degradation of hydrocarbons by the natural microorganisms that are already present in the soil, but the processes would take too long if the oxygen available to the microbes were lacking. Generation of Reactive Oxygen Species (ROS) such as hydroxyl radicals and sulfate radicals, which are directly involved in oxidative degradation of petroleum compounds complementing biological pathways. Desorption and mobilization mechanisms of nanobubbles can help overcome mass transfer limitations that can be a barrier to hydrocarbon remediation, enhancing bioavailability of the contaminant for biological and chemical remediation[28].

5.2 Pesticides and Herbicides

The high incidence of use, persistence and off-site movement make pesticides and herbicides in agricultural soils a serious environmental and health issue. Nanobubble technology is a proven solution to tackle these contaminants and keep soil healthy and productive. The combination of oxygen nanobubbles and graphene oxide incorporated biochar has been found to have multifunctional remediation abilities for pesticide residues such as cyromazine, plasticizers like bisphenol A and DEHP and flame retardants like diphenyl phosphate, in agricultural land. The combined biochar-nanobubble platform not only suppressed the bioavailability of contaminants but also promoted the oxidative degradation of contaminants with the ability to remove contaminants in a short period while retaining nutrient bioavailability and crop productivity for successive crops. By means of the interfacial enrichment mechanism, nanobubbles can provide sites for the accumulation and removal of amphiphilic pesticide compounds[29], [30]. Ultimately, nanobubbles with their sustained oxygenation and microbial stimulation mechanisms promote the biological degradation pathways, which are the cause of the ultimate mineralization of pesticide residues in soil systems. The combination with the phytoremediation techniques provides the possibility to grow the crops and remediate the pesticide contaminated

soils, thereby promoting the sustainability of agriculture and food security[31].

5.3 Phenolic and Industrial Organic Pollutants

The toxic, persistent and potentially groundwater contaminating nature of phenolic compounds and other industrial organic pollutants poses unique remediation challenges. Nanobubble-based solutions are well suited to tackle these contaminants, by combining oxidative and biological approaches. Nanobubbles generate hydroxyl radicals and other reactive oxygen species which allow for direct oxidative degradation of phenolic compounds, to break the aromatic ring which is a major source of persistence and toxicity[32]. The continuous aeration of polluted soils enhances the growth of aerobic microorganisms that are able to break down the phenolic compounds via oxidative metabolic routes. When using nanobubble treatment, soil physico-chemical properties (such as redox potential, soil surface chemistry) can be modified, which can lower the toxicity of the phenolic compounds and increase their bioavailability to be degraded. Hybrid systems combining nanobubbles with advanced oxidation processes such as ozonation and photocatalytic oxidation can be used to treat the most resistant pollutants present in industry by multiple mechanisms. From an industrial-application perspective, where cost considerations are critical, the cost-effectiveness and scalability of nanobubble generation make this attractive[33].

5.4 Chlorinated and Recalcitrant Organic Compounds

Some of the most recalcitrant soil contaminants are chlorinated organic compounds (COCs) which are resistant to biological degradation and can be found in groundwater and vapor intrusion. Nanobubble technology has some interesting avenues for targeting these compounds by oxidative means that break the carbon-chlorine bonds which contribute to the recalcitrance of these compounds. The formation of highly active species like hydroxyl radicals with standard reduction potentials that are high enough to oxidize chlorinated compounds offers direct degradation pathways in addition to or in place of

biological processes. When using nanobubbles in combination with other advanced oxidation process technologies, such as ozonation and electrochemical oxidation, the amount of radicals produced is increased and most recalcitrant compounds can be treated[34]. The nanobubble technology's ability to uniformly distribute and penetrate soil matrices also helps to overcome mass transfer barriers which hinder the effectiveness of oxidative treatments for chlorinated compounds. Nanobubbles allow for the continuous supply of oxygen and enable aerobic cometabolic degradation of chlorinated compounds by unique microbial communities to achieve sustainable and cost effective remediation solutions. Nanobubble chlorinated compound remediation can be customized by optimizing the type of gas, size of the nanobubbles and injection conditions for specific site conditions and contaminant profiles[35].

5.5 Emerging and Persistent Organic Contaminants

The presence of emerging organic contaminants, such as per- and polyfluoroalkyl substances, pharmaceuticals, PPCPs, and micro-plastics has gained attention as an important soil contaminant and a need for effective remediation strategies. Nanobubble technology has certain potential for dealing with these contaminants because of its ability to accumulate on interfaces and oxidize them. The amphiphilic structure of PFCs makes it possible for PFCs to spontaneously accumulate at the gas-liquid interface of nanobubbles, which provides a molecular basis for enrichment at the interface and the eventual removal thereof. Inside the nanobubbles the perfluorocarbon chain of these compounds may insert in a directionally way in the gas phase of the nanobubble; the anionic-head groups of these molecules may be arranged in an ordered way in the nanobubble-water interface and the result is an effective separation manner[18]. Reactive oxygen species generation is a possible oxidative degradation mechanism for pharmaceutical traces and other emerging contaminants which might be biologically non-degradable by nanobubbles. Nanobubbles could be combined with adsorption materials like

biochar and graphene oxide modified sorbents to develop hybrid systems that not only remove emerging contaminants, but degrade them. The use of nanobubble technology is versatile and adaptable, aligning with the complex and evolving challenges of emerging contaminants in soil systems[10].

6. Applications for Heavy Metals and Soil Restoration

6.1 Remediation of Pb, Cd, Cr, Hg, and As

The contamination of soils with heavy metals is a problem in particular ways because the metals are persistent, toxic, and can be variously 'speciated', such as lead, cadmium, chromium, mercury and arsenic. There are revolutionary ways to remove metal contamination using nanobubble technology, which include both metal mobilisation and metal immobilisation strategies. Nanobubbles generate ROS that may change the speciation of the metals, resulting in changes in solubility, mobility and toxicity. Arsenic has also been used with the interfacial oxygen nanobubble technology and injection of O₂ nanobubbles to remediate sediment by increasing the toxicity of the arsenic, converting the less mobile, less toxic, arsenite species into the more mobile, less toxic, arsenate species[18]. The combined sorption and oxygenation effect on the binding of metals at the surface of biochars can be applied to mitigation of the Cu transfer to rice, as oxygen nanobubble loaded biochars not only immobilize Cu, but also enhance rice growth in Cu contaminated soils. Application of nanobubble (NB) modifies the soil redox potential, which helps to control the behavior of redox sensitive metal in the contaminated soil by changing their speciation and mobility. Nanobubbles and biochar or other sorbents are combined into an effective system for metal immobilization, which lowers the bioavailability of metals and plant uptake. Optimization of gas type, bubble properties and treatment conditions can tailor the application of nanobubbles for metal remediation to a particular metal contaminant, type of soil, and remediation goal[2], [18].

6.2 Metal Mobilization, Immobilization, and Speciation

Mechanisms of nanobubble effects on metal behaviour in soils involve mobilization, immobilization, and speciation transformations, which are predominant based on soil conditions, metal properties, and treatment parameters. Nanobubbles promote metal mobilisation via many mechanisms, such as the acidification effect (promote the solubility of metals) and the surface charge effect (reduce the adsorption of metals) and the competitive desorption effect (displace metals from soil sorption sites). On the other hand, immobilization mechanisms are the oxidation of reduced metals to less soluble ones, reactions of precipitation caused by pH changes, and the increased sorption to soil components by the nanobubble treatment[10], [36], [37]. The speciation changes caused by the nanobubbles have the potential to change the toxicity and the mobility of metals by many orders of magnitude, as for example the oxidation of arsenite to arsenate, which reduces its toxicity by some tenfold. The combination of the mobilization and immobilization techniques allows selective removal of some metals and ensure the stabilization of others thus enabling comprehensive metal management strategies. Nanobubbles are combined with biochar and other soil amendments to form metal immobilization systems which decreases the bioavailability and plant uptake of metal; this helps to ensure safe agricultural production on contaminated soils. It is crucial to know both the mechanisms of mobilization and immobilization to understand how to best remediate metal pollution[38].

6.3 Influence on Metal–Mineral Interactions

Heavy metal–soil mineral interactions plays a crucial role in determining the mobility, bioavailability, and remediation potential of heavy metals, and the application of nanobubbles can significantly change the nature of these interactions. Nanobubbles will form at soil interfaces such as mineral surfaces with goethite, pyrite, quartz etc. and will affect the microenvironment of the sorption and desorption

of metals. The electric fields at the interface created by charged nanobubbles can lead to changes in the electrostatic interactions between metal and charged mineral surfaces and thus affect the sorption equilibria[39]. Oxygen formed by the nanobubbles can oxidize reduced minerals, like pyrite, and release associated metals while also providing new sorption sites. Surface chemical changes by reactive oxygen species generation can lead to the change of sorption mechanisms of metals, which can make the amount of metal retained in the mineral either higher or lower, depending on the mineral-metal system. The nucleation of nanobubbles at mineral surfaces (as shown in the microfluidic experiments, in which quartz was found to generate the largest number of nanobubbles among the minerals studied) forms pockets of increased reactivity that determine the behavior of metals. This knowledge of mineral specific effects is crucial for the prediction of nanobubble performance for metal remediation in a variety of soil types[2], [40].

6.4 Nanobubbles for Saline and Degraded Soils

Saline and degraded soils (high soluble salt concentration, poor soil structural condition, low soil biological activity) pose unique challenges for restoration and agricultural purposes. Nanobubble technology provides a number of potential solutions to address these soils in a number of complementary ways. By creating oxygen for the plant and strengthening the root system, application of nanobubbles can alleviate salt stress for plants, allowing them to establish and grow where previously marginal soil would not allow other plants. The nanobubble treatment changes the soil structure for better drainage and leaching salts and decreases the salinity of soil[10], [30]. In disturbed soils, increased microbial activity promotes the build-up of soil organic matter, nutrient cycling and soil structure development, leading towards the restoration of soil functions. The potential of combined nanobubble/bioremediation techniques shows great salinity reduction and increased crop production, opening ways for saline agricultural land restoration to productive use. Adopting nanobubbles in combination with biochar and

other soil amendments offers a holistic soil improvement and management solution for sustainable intensification of agriculture on degraded soils. The economics of using nanobubbles for saline soil restoration is dependent on the value of land, availability of water and the production potential of the crops with many conditions having favorable economics[41].

6.5 Restoration of Soil Health and Ecosystem Functions

Nanobubble technology does not only help remove the contaminants from soil it also helps in restoring soil health and ecosystem processes vital for sustainable land use and environmental quality. Soil health restoration is defined as soil health improvement in soil physical, chemical and biological properties such as soil structure and porosity, water infiltration and soil water, microbial biomass, microbial diversity and microbial activity. The soil health benefits of nanobubbles include an increase in soil oxygen and aerobic microbial activity, better nutrient cycling and availability, better soil aggregation and porosity, better plant growth and root development, and better microbial-plant relationships. These combined mechanisms result in the restoration of ecosystem functions, such as sequestration of carbon, nutrient cycling, water purification, and support of biodiversity. Agricultural soil improvement, mine spoil remediation and ecosystem restoration are just a few examples of applications for nanobubbles to be used in soil restoration. The energy input, economic viability, and potential impact on the environment add to the sustainability of nanobubble-based restoration, and must be carefully evaluated for each application context[8], [42].

7. Hybrid Nanobubble-Based Remediation Strategies

7.1 Nanobubbles Combined with Bioremediation

The combination of nanobubble technology with bioremediation technologies produces synergistic systems which overcome the limitations of each technology while taking advantage of its strengths.

The nanobubble-induced increase in oxygen availability, contaminant bioavailability and nutrient cycling increases the bioremediation, either by bioaugmentation with specific degrader strains or by biostimulation of existing indigenous microorganisms. The constant presence of oxygen supplied by the nanobubbles enables the oxidative metabolic pathways required for most organic contaminants to be degraded and thus establishes aerobic zones in former oxygen deficient soil matrices. The mechanisms of contaminant desorption and mobilization by nanobubbles make the contaminants more readily available to the degrading microorganisms, which is a problem that is encountered with bioremediation when contaminants are not available for the degraders to work[43]. The application of nanobubbles stimulates specific functional microbial groups, such as aerobic hydrocarbon degraders and co-metabolic dechlorinators as a result of which the metabolic diversity and degradation capabilities of the soil community is increased. Combined nanobubble and biochar systems offer both continuous oxygenation and contaminant sorption, which aid in microbial degradation and decrease contaminant mobility. Promised for comprehensive biostimulation systems, where the various limitations on growth are solved with only one single treatment, is the use of nanobubbles in combination with addition of nutrients and adjustment of the pH[44].

7.2 Nanobubbles and Phytoremediation

Nanobubble technology and phytoremediation are thus able to be combined together, offering strong systems that exploit the natural functions of the plants in the process of removal, stabilization and breakdown of contaminants and at the same time overcome the limits of phytoremediation processes. Plants used for phytoremediation, which removes, stabilises or breaks down contaminants, can be improved by nanobubble induced plant health, root growth and bioavailability of contaminants. More roots, created by nanobubble oxygenation, grow into a greater mass of soil and the more active roots take in or break down contaminants more quickly. The enhanced rhizodegradation of organic

contaminants in the plant rhizosphere as a result of nanobubbles stimulating the microbial communities in that zone. Nanobubble treatment enhances the physico-chemical properties of soils, such as oxygen availability, nutrient cycle, thus improving soil environment for plant growth in polluted soils. Nanobubbles have been proven to enhance phytoremediation for several plant species and several contaminant types, including beneficial response by the halophytic plant *Tamarix smyrnensis* being used in the metal contaminated mine spoils. By combining nanobubbles with biochar and other soil amendments, holistic solutions are achieved that empower plants to grow and detoxify contaminants in challenging soil conditions[30], [45], [46].

7.3 Nanobubbles with Advanced Oxidation Processes

Combination of nanobubbles with the advanced oxidation processes results in hybrid systems that can be used to remove the toughest organic contaminants by multifaceted oxidation processes. AOP techniques such as ozonation, photocatalytic oxidation and Fenton reactions produce highly reactive species that have the ability to mineralize organic contaminants by oxidatively cleaving chemical bonds. The use of nanobubbles for advanced oxidation processes (AOP) increases the gas dissolution, reactive species generation, and accessibility of contaminants to the reactive species, thus boosting the efficacy of the process. Nanobubbles add extra oxidative capacity, due to reactive oxygen species generation, to that of the advanced oxidation process. The interfacial effects of nanobubbles such as electrostatic enrichment and microenvironment modification improve the efficiency of adsorption coupled oxidation processes. The synergy of nanobubbles and the use of ozone as one of the most powerful AOP has showed significant promise for water and soil treatment applications. The removal of 2,4-dichlorophenoxyacetic acid using ozone micro-nano bubbles and biochar adsorption works in synergistic mode and it is a combination of adsorption and catalytic oxidation mechanism[47], [48].

7.4 Nanobubbles–Ozone and Other Reactive Gas Systems

The production of nanobubbles using the oxidizing gases of ozone, oxygen and hydrogen peroxide forms systems that offer a higher capacity to oxidize contaminants. The ozone nanobubbles are an ideal way to efficiently degrade the contamination in the soil and water system, combining the potential of the high oxidative property of ozone and the mass exchange of nanobubbles. The use of ozone nanobubbles in contaminated soils can rapidly oxidise the contaminants by producing hydroxyl radicals and other reactive species which will be effective for compounds that are not biodegradable[3], [49]. The long-term dissolution of ozone in nano-size bubble increases the contact time between oxidant and contaminant for the efficient treatment. Synergistic effects of ozone nanobubbles with catalytic materials such as metal oxides and biochar promote the generation of radical and the treatment efficiency. When nanobubbles are used in conjunction with electrolyzed catalytic systems, mixed oxidant systems that include chlorine species, sulfate radicals and hydroxyl radicals are created, which can be used to achieve broad-spectrum oxidative capacity for complex mixtures of contaminant. The choice of the type of gas to generate nanobubbles offers flexibility to meet certain contaminant profiles by modifying the chemical reactivity[50].

8. Optimization, Scalability, and Sustainability

8.1 Influence of Soil Properties on Nanobubble Performance

Soil characteristics which affects the generation, transport, stability, and contaminant interactions of nanobubbles has a significant impact on the effectiveness of soil remediation using nanobubbles. The overall soil texture (sand/silt/clay ratio) influences the pore size distribution, the hydraulic conductivity and the potential soil textural filtering/attachment of nanobubbles during transportation in the soil. The ability of soil interfaces to produce nanobubbles is also dependent on soil hydrophobicity, as quantitative relations showed positive correlation between soil hydrophobicity

and nanobubble concentration. Surface chemistry effects, contaminant sorption and modulation of microbial activity of nanobubbles is dependent on the presence or absence of organic matter[18]. pH and ionic strength of the soil can affect the surface charge and the colloidal stability of nanobubbles, which impacts their transport and reactions to interface. Soil minerals such as iron oxides, clay minerals and carbonates offer specific (active) surfaces for the nucleation of nanobubbles and control the degree of the interaction between soil contaminants and nanobubbles. The distribution and movement of the nanobubbles in porous media are controlled by soil moisture conditions such as saturation degree and water content. Knowing these soil specific effects will be crucial to prediction of nanobubble performance in different types of soil as well as to develop appropriate application strategies[46].

8.2 Optimization of Gas Type, Bubble Size, Pressure, and Injection Conditions

By systematically varying operational parameters such as the bubble size, gas type, injection conditions and pressure, the performance of nanobubble based soil remediation can be optimized. The reactivity and biological effect of nanobubbles is dependent on the type of gas used: oxygen for aerobic stimulation, ozone for oxidative degradation, and carbon dioxide for pH and nutrient level changes. The distribution of bubble sizes will affect the transport in porous media: small bubbles will be more penetrating and uniformly distributed but may be less stable in some conditions[6]. Nucleation rates, bubble size, and concentration are determined by gas supersaturation and the pressure at which the bubbles are formed; increasing supersaturation tends to increase the number concentration of bubbles. Variables affecting nanobubbles' spatial and temporal distribution in the soil profile under injection conditions and the efficacy of remediation are flow rate, injection duration and frequency. Experimental and modeling work needs to be systemically carried out to understand which application parameters are most effective for a particular type of soil and contaminant concentration. Standardized operating protocols

and standardized performance metrics will play a critical role in comparing results from different research projects and in helping to implement these findings at the field level[51].

8.3 Pore-Scale Modeling and Reactive Transport

Comprehending and predicting behaviour of nanobubbles in porous soil systems needs some more sophisticated modelling approaches that involve pore-scale phenomena as well as reactive transport processes. Many mechanisms control transport and retention of nanobubbles in saturated porous media, including advection, dispersion, attachment, straining, and detachment, which vary in importance based on the soil properties and flow conditions. The influence of pore size distribution and colloidal fines in the nanobubble transport behavior has been shown, with bubbles being retained in smaller pores and with higher content of colloidal fines. Classical nucleation theory can be used to theoretically investigate the nucleation of an air bubble at the soil interface, which offers the means to understand where and under what conditions bubbles will nucleate spontaneously in soil systems. To predict performance of remediation, multiple processes such as nanobubble generation, transport, contaminant interactions, Reactive Oxygen Species generation, and microbial stimulation must be included in a Reactive transport model. Combining pore-scale modeling with field-scale transport models allows the laboratory results to be scaled up to the field and optimization of remediation designs. A technology work priority under way is the development and validation of nanobubble behavior predictive models that will enable technology implementation in soils[52], [53].

8.4 Laboratory-to-Field Scale Translation

However, there are significant challenges in the process of scaling up nanobubble technology from laboratory and greenhouse research to field scale applications, which need to be overcome for successful deployment of the technology. To transfer the generation of nanobubbles from a small laboratory system to a field-scale system, engineering solutions need to be developed to

ensure the quality and concentration of the bubbles while ensuring the treatment capacity. Due to the heterogeneity of field soils, there is variability not represented in laboratory-based studies conducted on repacked or homogenized soil samples and thus, field validation studies are necessary at different site conditions[54], [55]. The costs and benefits of applying the treatment in the field (energy costs, equipment and operation cost) versus the worth of the remediation or soil improvement must be taken into account for economic feasibility. The length of time and frequency of nanobubble application needed for effective field-scale remediation needs to be monitored to determine if contaminant concentrations, soil properties and ecosystem responses have been effective. Cost of implementation can be lowered, and use of the nanobubble technology can be made easier, by using it in conjunction with existing agricultural or remediation infrastructure. It is important to establish field demonstration projects and to develop case studies to grow confidence in the technology and to offer practical guidance for implementation[56].

9. Environmental Risks, Knowledge Gaps, and Future Research

9.1 Ecotoxicological and Soil-Microbiome Considerations

Ecotoxicological effects of nanobubbles on soil organisms and long-term effects on soil microbiomes are important questions that should be systematically investigated. Reactive oxygen species (ROS) generated by nanobubbles may have a positive impact on contaminant degradation, but if generated to a high concentration, they can have an oxidative stress effect on soil organisms and could impact soil fauna, the microbial community and the health of plants. Nanobubble treatment can be expected to impact soil physics and chemistry, as well as potentially alter the structure of the soil ecology, leading to a change in function for some organisms and the elimination of others[57]. Long-term effects of nanobubble-induced alterations in soil properties and microbial community needs to be evaluated by longer timescale monitoring. The effects of

nanobubbles on soil organisms will probably be case-specific and depend on the type of soil, the nature of the gas used, the intensity of the application, and should therefore be evaluated case by case. These changes in soil microbial community diversity and function induced by nanobubbles and their impact on soil fertility, vegetation health and ecosystem services must be explored in detailed ecological studies. Long-standing standards, procedures, and guidelines for evaluating the ecotoxicity of nanobubble technology and for assessing risk would be important to assist in the regulatory acceptance process[10], [51].

9.2 Contaminant Remobilization and Secondary Pollution Risks

The mobilization of contaminants via nanobubble treatment can increase bioavailability and removal of contaminants from the environment, but can also present a risk of contaminant remobilization and potentially cause secondary pollution. If contaminants are mobilized from soil surfaces and released into soil water, increased potential for groundwater contamination may result when the contaminants are not degraded or removed thereafter. Migration of mobilised contaminants, through ground water or surface runoff, is a potential pathway of off-site migration that should be taken into account in site management. Treatment completeness and product toxicity should be considered because reactions between contaminants and ROS can generate transformation products that are potentially more mobile or toxic than the contaminants[58]. Nanobubble-induced oxidation or acidification may lead to release of metals from mineral phases, resulting in increased metal mobilisation and potential for transport, highlighting the need for balances in metal management strategies between mobilisation and removal/immobilisation. Nanobubble-based remediation strategies should be designed to account for the management of mobilized contaminants to avoid secondary pollution (e.g., downgradient capture or in situ stabilization). To manage remobilization risks, the use of nanobubble treatment in conjunction with

containment and monitoring strategies is crucial[18].

Conclusions

The status of nanobubble based soil remediation is as follows: The research base is quickly expanding; there are some impressive lab and greenhouse results; and there are some early field demonstrations with significant potential to explore more difficult soil remediation problems. Soils treated with nanobubbles are reported to show growth increases in the plant of 10 to 50 percent, and there are numerous studies of very high efficiency of removal from a variety of contaminants of 75 to 98 percent. However, transfer of these promising results to field scale applications is still in its infancy, as only a few field-scale validation studies have been conducted and many knowledge gaps remain. It has been identified as having potential applications for technologies where traditional remediation methods are restricted by the limitations in mass transfer, lack of oxygen, or lack of bioavailability of the contaminant, such as hydrophobic organic contaminant in fine textured soils and in oxygen limiting agriculture soils. Current commercialization levels are relatively limited due to economic, regulatory and the absence of proven implementation procedures but hybrid systems with the use of bioremediation and phytoremediation, and with the use of advanced oxidation offer increased capabilities and may perhaps lead to speedier adoption of these technologies.

There has been significant development of the mechanistic understanding and technological capabilities that can be continued as a basis for further development. The mechanisms of nanobubble stability, as suggested by the surface charge driven repulsion and gas shielding, have helped in designing their applications, and the generation of nanobubbles at the soil interfaces has helped in finding out the capacity of soils to generate nanobubbles under the right conditions. Precise measurement of nanobubble properties in complex soil matrices is possible and provided by advanced characterization techniques (e.g., nanoparticle tracking analysis and microfluidic

platforms), and optimisation of nanobubble generation has yielded efficient and scalable systems. The mechanisms of degradation for contaminants through the generation of reactive oxygen species and enhancement of mass transfer are also shown to provide scientific rationale for their use, and influences of soil properties are identified for more effective application design.

The priorities for research are field scale validation, long term performance assessment, ecotoxicological evaluation and optimization of hybrid remediation. Field-scale studies should be done to verify what occurs in the lab and to identify implementation issues, and long-term monitoring should be conducted to examine persistence of remediation, recovery of soil health, and possible delayed impacts to the environment. Extensive ecotoxicological investigations need to be done to determine safe conditions of use, and systematic investigation of optimal combinations of hybrid application (bioremediation, phytoremediation, biochar, and advanced oxidation) should be conducted. To build more effective design, predictive models for the incorporation of transport, reactivity, and the biological effects would be necessary, and standardized protocols and performance measures would be important for the comparison of technology and guidance for implementation. Efficient generation systems, life-cycle assessment, and the adoption of AI, digital twinning, and smart monitoring are all crucial to the pathway to scalable, sustainable, and precision remediation. The unique properties and wide variety of applications of nanobubble technology have transformative potential in sustainable soil remediation to support sustainable management of land and the environment.

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