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Review

Systematic Review of Poultry Slaughterhouse Wastewater Treatment: Unveiling the Potential of Nanobubble Technology

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Abstract: Aeration is crucial for the biological decomposition of organic compounds in wastewater treatment. However, it is a highly energy-intensive process in traditional activated sludge systems, accounting for 50% to 75% of a plant's electricity consumption and making it a major cost driver for wastewater treatment plants. Nanobubbles (NBs), characterized by their tiny size with diameters less than 200 nm, have emerged as a potential alternative to the low efficiency of aeration and high sludge production in aeration systems. NBs proved effective in removing COD and other pollutants from wastewater. For example, when applied in flotation, aeration, and advanced oxidation, NBs achieved up to 95%, 85%, and 92.5% COD removal, respectively. Considering the recent advancements in wastewater treatment, a compelling need arises for a thorough investigation of the effectiveness and mechanisms of nanobubbles in this field. This systematic review summarizes recent advancements in understanding nanobubbles (NBs) and their unique properties that enhance physical, chemical, and biological water and wastewater treatment processes. Moreover, this study reviews various methods for generating NBs and provides an in-depth review of their applications in wastewater treatment, with a particular focus on poultry slaughterhouse wastewater (PSW) treatment.

Keywords: nanobubble; biological treatment; aeration; chemical oxygen demand; poultry wastewater treatment; poultry slaughterhouse wastewater

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1. Introduction

Water stands as a vital element crucial for all forms of life, playing a central role in sustainable development. Its significance extends to socio-economic prosperity, the well-being of ecosystems, and the very survival of humans. The escalating demand for water has underscored the urgency of effective water management. Simultaneously, inadequate wastewater treatment practices in certain regions have exacerbated the improper discharge of wastewater into the environment, contributing to the pollution of natural water resources. Consequently, global efforts have increasingly shifted from merely disposing of wastewater to emphasizing water reuse and recycling, driving advancements in wastewater treatment technologies capable of recycling and reusing wastewater [1].

Industries such as poultry slaughterhouses significantly contribute to freshwater consumption. The high demand for poultry meat consequently amplifies freshwater consumption by poultry processing plants [2]. Poultry processing plants release substantial volumes of wastewater into the environment due to their extensive use of freshwater for ongoing activities such as meat cutting and rinsing. This wastewater is highly contaminated, featuring organic matter measured by biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Moreover, the wastewater contains elevated levels of nitrogen and phosphorus components, encompassing substances such as blood, fats, oil, grease, and proteins [3]. The attributes of poultry slaughterhouse wastewater (PSW), as well as guidelines for effluent discharge as set by the South African National Water Act 36 of 1998, are outlined in Table 1. It is essential to treat PSW to meet or fall below the specified standard limits since the parameters of untreated PSW substantially exceed the acceptable thresholds established in the National Water Act 36 of 1998.

Table 1. Characteristics of raw poultry slaughterhouse wastewater [3] vs. general discharge limits [4].

Parameter	Significance	PSW	General Discharge Limits as Set in the National Water Act 36 of 1998
pH at 25 °C	Measure of acidity and basicity	6.3–7.3	5.5–7.5
COD (mg/L)	Organic substrate for microbial growth	5126 ± 2534	75
TSSs (mg/L)	Measure of particles in wastewater	1654 ± 1695	25
FOG (mg/L)		715 ± 506	2.5
Ammonium as N (mg/L)	Nutrient source for irrigation	216 ± 56	6
Nitrates as N (mg/L)	Nutrient source for irrigation	3.33–4.45	15
Nitrites as N (mg/L)	Nutrient source for irrigation	-	15
Total phosphates as P (mg/L)	Nutrient source for irrigation	-	10

Moreover, the improper discharge of inadequately treated PSW poses a substantial risk of contaminating freshwater sources. This poses potential environmental and health hazards, including river deoxygenation, groundwater pollution, eutrophication, and the potential spread of waterborne diseases [5].

Typically, PSW conventional treatment approaches involve physical, chemical, and biological methods. However, these traditional techniques encounter challenges such as the absence of nutrient recovery, frequent reliance on chemical cleaning agents, and the deterioration of valuable compounds within the wastewater. Consequently, alternative methods, including nanobubble (NB) technology, are being investigated for PSW treatment. This systematic literature review focuses on conventional PSW treatment and identifies the potential application of NB technology in PSW treatment.

2. Materials and Methods

In this study, a systematic methodology is followed in conducting the literature review, adhering to transparent and explanatory practices with the objective of ensuring the scientific rigor and value of its findings. It follows the crucial steps recommended by the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines [6].

2.1. Information Sources and Search

In adherence to the systematic review principles, an exhaustive search was undertaken to identify all relevant articles published until January 2024. This search spanned two electronic databases as primary sources (Scopus and ScienceDirect). The search string was constructed using keywords such as "poultry*", "wastewater", "treatment", and "nanobubble".

2.2. Selection of Studies

The process followed during the selection of studies is depicted in the flowchart in Figure 1. In the initial phase, the search yielded 606 records from the databases, including 16 documents that were over 10 years old. Following an initial screening of abstracts, 300 articles were eliminated due to their lack of relevance to wastewater treatment. A comprehensive review of the full texts of the remaining 290 papers resulted in the exclusion of 187 studies that did not feature case studies.

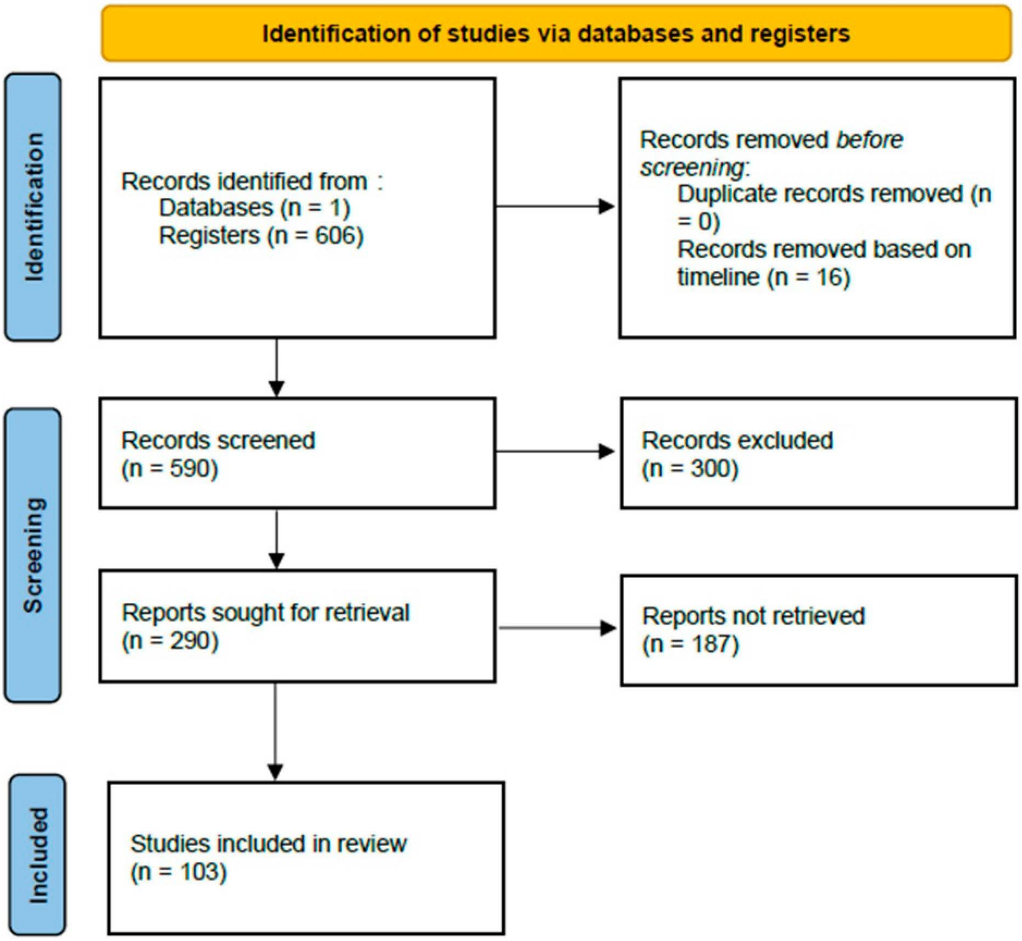

Figure 1. Flowchart of study selection based on PRISMA.

2.3. Data Extraction, Bibliometric Mapping, and Statistical Analysis

Crucial details from the selected articles, including author names, publication year, title, abstract, keywords, and source, were extracted from the databases and organized in a format compatible with Microsoft Excel worksheets. The compiled data were analyzed using VOSviewer to conduct bibliometric mapping, unveiling significant themes within the research field of nanobubble technology and poultry wastewater treatment. VOSviewer aided in visualizing interconnections among the gathered data, clustering them based on keywords that appeared at least four times.

Figure 2 displays a co-occurrence analysis of keywords, visually depicting the relationships among terms based on their frequency and organizing them into distinct color-coded clusters. In this analysis, the blue nodes group keywords associated with "water treatment" linked to membrane processes such as nanofiltration. The purple cluster encompasses keywords related to flotation processes. The red nodes cluster terms related to aeration processes, connected to the microbial community, flotation, and dissolved air flotation, indicating a growing interest in NB aeration in biological processes. The orange cluster underscores the properties of NBs, mostly their stability and the zeta potential. The green cluster relates to advanced oxidation processes (AOPs), emphasizing using NBs and ozone as oxidants. The presence of the keyword "generation" in this context indicates the different generation methods for NBs.

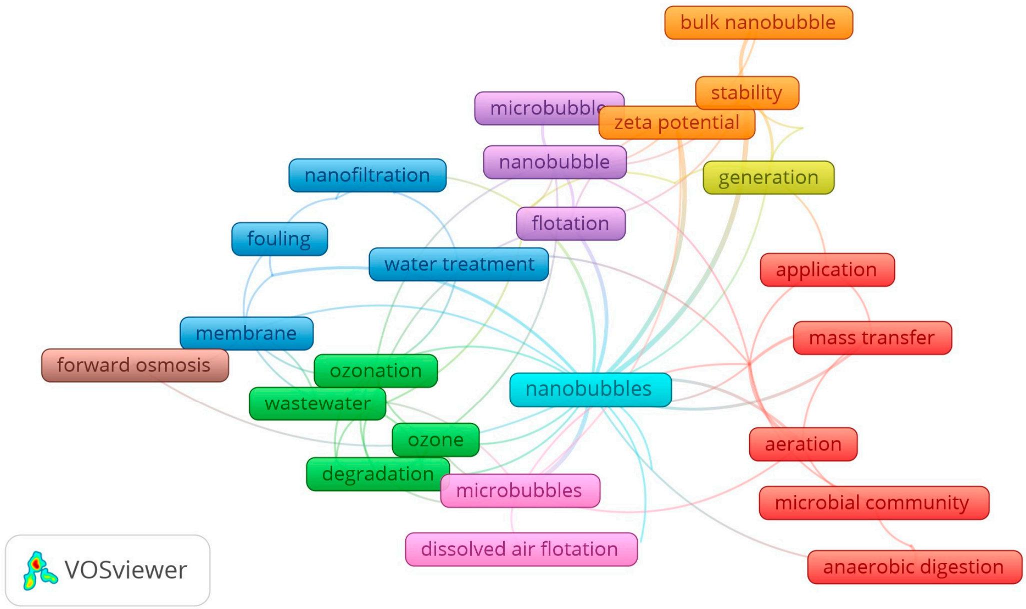

Figure 2. Co-occurrence analysis of the authors' keywords.

3. Nanobubble Technology

3.1. Bubble Size

Numerous researchers have categorized bubbles based on their sizes, distinguishing nanobubbles (NBs) (with a diameter of <200 nm), fine bubbles (FBs) (with a diameter of 200 nm–10 μm), microbubbles (MBs) (with a diameter of ≤50 μm), and macrobubbles (with a diameter of 2–5 mm) [7–9]. ISO 20480-1 [10], on the other hand, classifies bubbles based on their volume equivalent to diameter. In this classification, bubble sizes are denoted as micro, fine, and ultrafine bubbles/nanobubbles, covering the ranges of 1 to 100 μm, less than 100 μm, and less than 1 μm, respectively [9,11].

3.2. Fundamental Properties of NBs

Table 2 outlines the specific properties of various bubbles based on their diameters. The unique properties of NBs facilitate the enhancement of chemical reactions and physical adsorption by improving mass transfer efficiency at the liquid–gas interface [12]. According to Phan et al. [12], the high stagnation of NBs in the liquid phase contributes to increased gas dissolution above supersaturation in water.

Table 2. Properties of different bubbles according to their size [13].

Bubble Property	Macrobubbles	Microbubbles	Nanobubbles
Zeta potential	Low	High	Higher
Free radicals	Low	High	Higher
Mass transfer efficiency	Low	High	Higher
Bubble stability	Unstable	Stable	Stable
Rising velocity	Fast	Slow	Slower
Rising time	Short	Long	Very long
Oxygen transfer process	Inefficient	Efficient	Efficient
Internal pressure	Low	High	Higher

3.2.1. Negative Zeta Potential

According to Gurung et al. [11], zeta potential (ZP) refers to the electric potential exhibited by suspended particles, such as gas bubbles, which may result in either attraction or repulsion between them. It arises at the interface between the particles and the liquid medium. The level of colloidal dispersion stability can be gauged by the value of the ZP. A higher absolute ZP value signifies that the solution or dispersion is more stable, as it possesses a greater resistance to agglomeration, as elaborated by Shangguan et al. [14]. Typically, bubbles present in distilled water carry a negative charge owing to the presence of hydroxyl ions (OH^-) adsorbed at the interface between the gas and liquid phases [15].

ZP is influenced by various factors, including viscosity, bulk solution density, electrolyte concentration, chemical surfactants, pH, and temperature. When gas flow rates are controlled and sufficient energy or pressure is provided, bubbles exhibit high ZP values, regardless of the gas type [16]. Takahashi et al. [17] highlighted the significance of adsorbed OH^- and H^+ in influencing the charge at the gas–water interface. The electrostatic force leads to the attraction of electrolyte ions to the interface, generating an electrical double layer.

3.2.2. Ability to Generate Free Radicals

The collapse of NBs induced by ultrasonic waves triggers the generation of free radicals, particularly hydroxyl radicals (OH^-), known for their potent oxidizing capabilities [18]. This generation of free radicals is a primary reason for employing NBs in the oxidative treatment of wastewater. The collapse process leads to an increase in the ZP, contributing to the formation of free radicals. The proposed mechanisms encompass the entrapment of excess ions at the NB interface, the abrupt disappearance of the gas–liquid interface during bubble collapse leading to a pronounced environmental alteration, and the generation of free radicals attributed to an instantaneous high density of ions [19].

In other terms, the collapse of bubbles results in the elimination of the gas–liquid interface. During the self-pressurizing process of NBs, a remarkably high concentration of charged ions accumulates at the interface, aiming to dissolve, and this accumulation, upon dissolution, rapidly releases the chemical energy responsible for generating hydroxyl radicals (OH) [20]. The stability of cavitation bubbles is indicated by the efficiencies of free radical formation through the thermal decomposition of water in a hot spot. The presence of MBs in the solution can impact the formation of free radicals through ultrasound, potentially enhancing the generation of hydroxyl radicals (OH) [21].

3.2.3. Gas Mass Transfer

Enhancing the efficiency of mass transfer between gas and liquid is achievable with NBs since the mass transfer rate of a gas is dependent on the mass transfer area of gas–liquid phases. NBs offer a significantly higher mass transfer area, leading to the potential for the gas dissolution rate in water to reach a supersaturated state [20]. The reduction in bubble radius, coupled with an increase in internal pressure, contributes to an increased mass transfer rate of NBs to the surrounding liquid [22]. Additionally, the diffusion rate of gas moving from a higher-pressure region to a lower-pressure region is directly proportional to the pressure gradient [23]. Consequently, utilizing smaller bubble sizes could augment the efficiency of gas transfer.

The success of aerobic biodegradation relies on dissolved oxygen (DO) as the electron acceptor and the ability to deliver oxygen to microorganisms. Consequently, the efficacy of aeration may be constrained by the rate at which oxygen transfers from gas to liquid and the oxygen consumption rate by microbes. Employing smaller-sized bubbles, such as MBs, has the potential to enhance gas transfer efficiency and augment beneficial reactions in water treatments [24]. Liu and Tang [25] verified that micro-nanobubbles (MNBs) can enhance the DO levels and oxygen mass transfer rate, leading to an accelerated removal of pollutants. They determined that in comparison to air MBs, the rate at which DO is transported by oxygen NBs was approximately 125 times quicker during the highest DO level, which was nearly three times greater, and the increased endurance of DO was 16 times longer than that of air MBs. The choice of gas has a notable impact on stagnation time, with oxygen bubbles, encompassing both macrobubbles and MBs, displaying residence times at least four times longer than air bubbles [25].

3.2.4. Stability of Nanobubbles

The stability of NBs is determined by the extent to which they persist in a solution [20,24]. Enhanced stability is advantageous as it prolongs the period for gas mass transfer into the water, ranging from 60 min to several months for NBs [24]. The minimal rising velocity, attributed to Brownian motion, and the subdued buoyancy forces contribute to the increased stability of these bubbles. By maintaining higher pH levels with an abundance of OH^- ions, stable and smaller NBs with elevated ZP values can be generated [16]. Azevedo et al. [26] explained that the stability of NBs can be attributed to various mechanisms, encompassing those expounded in gas density theory, liquid height theory, Knudsen gas theory, and line tension theory. Moreover, the dynamic equilibrium model and surface forces play roles in the comprehensive stability of NBs.

The presence of an electrically charged interface between the liquid and gas induces repulsion forces that impede bubble coalescence, thereby contributing to the stability of nanobubbles (NBs). Furthermore, the high concentration of dissolved gas in the water facilitates the preservation of a minimal concentration gradient between the gas and the liquid.

3.3. Generation of Nanobubbles

NBs can be produced in a liquid by adjusting gas pressure, ultrasonic intensity, or stirring intensity. The most popular methods for generating NBs include mechanical stirring, gas dissolution release, pressure variation, and cavitation. Additionally, methods such as microfluidic systems and nano-porous membranes can be employed for the preparation of NBs. These methods are reviewed in Sections 3.3.1–3.3.6 and are summarized in Table 3.

Table 3. Summary of nanobubble generation methods.

Method	Principle	Advantages	Disadvantages	References
Mechanical stirring	Iterative rotational stirring facilitates bubble formation due to shear forces and turbulence.	Rapid generation; stability for an extended period.	Limited control over size distribution.	[27]
Venturi-based	Utilizes converging and diverging flow to induce pressure changes, leading to bubble formation.	Simple design; controllable bubble size with divergent angle and liquid flow rate.	Limited uniformity in bubble size.	[28,29]
Porous membrane	Compressed gas is introduced through membrane pores into a liquid phase, generating bubbles on the membrane surface.	Controlled bubble size by adjusting membrane pore size and liquid flow velocity.	The influence of membrane properties on bubble size needs consideration.	[30]
Acoustic cavitation	Induces local negative pressure in liquid through high-speed propeller rotation or high-intensity sound waves, forming micro- and nano-scale bubbles.	High energy efficiency; scalability.	Potential for bubble coalescence and fusion; sensitivity to organic solvents.	[31,32]

Table 3. *Cont.*

Method	Principle	Advantages	Disadvantages	References
Microfluidics-based	Regulates the flow of mixed gas and liquid in microfluidic chips, resulting in the formation of MBs that evolve into NBs.	Precise control over size and uniformity; adjustable by gas ratio.	Requires specialized equipment; complexity in setup.	[33]
Hydrodynamic cavitation	Alters flow velocity to induce cavitation, causing pressure fluctuations and generating NBs.	High energy efficiency, low cost, and scalability.	Requires optimization for specific applications.	[34]

3.3.1. Mechanical Stirring Method

The generation of NBs through mechanical stirring entails subjecting a liquid phase with surfactants to repeated rotational stirring using a mechanical system. This process induces high shear forces, intense turbulence, collision effects, and hydrodynamic cavitation, fostering interactions between the gas and liquid phases and resulting in bubble formation. These bubbles, undergoing multiple agitation cycles, undergo continuous shearing, leading to the gradual creation of smaller bubbles and the eventual formation of NBs [27].

In experiments conducted by Etchepare et al. [35] on NB preparation through the mechanical stirring method, they used a pump and circular column under varying pressures and air–liquid interfacial tensions. They found that this technique could swiftly produce stable NBs that maintained their stability for over 60 days. Additionally, Senthilkumar et al. [27] generated NBs using mechanical stirring in heat transfer oil. The produced NBs had diameters of less than 200 nm, contributing to improvements in the thermal conductivity and viscosity of the heat transfer oil.

3.3.2. Venturi-Based Generation

The Venturi bubble generator comprises three main elements: a narrowing entrance, a central throat, and an expanding outflow [29]. In this procedure, gas is introduced into the Venturi tube simultaneously with water, either through the narrowing entrance [36] or at the throat section [28].

The mechanisms of bubble generation in a Venturi-type bubble generator were explored by Zhao et al. [29], and they observed a pressure decrease in the throat region, leading to an increase in bubble velocity. Subsequently, the air bubbles undergo swift deceleration as they enter the widening outflow section, experiencing pressure recovery. The difference in flow velocities between the liquid phase and air bubbles creates a shock wave characterized by intense shear forces, causing the deformation of bubbles and the transformation of large bubbles into numerous smaller ones [29].

The divergent angle plays a crucial role in determining the performance of a Venturi-type bubble generator, as demonstrated by Agarwal et al. [7] and Li et al. [28]. They found that an increase in the divergent angle results in a reduction in bubble size. Additionally, Huang et al. [37] highlighted that the liquid flow rate is a key parameter influencing bubble size and distribution. A more uniform bubble size distribution can be achieved by increasing the liquid flow rate.

3.3.3. Porous Membrane Method

Porous membrane bubble generation involves introducing compressed gas from the outside of the membrane through its pores while a liquid phase flows inside the membrane, generating shear force to create bubbles on the membrane surface [38].

Kukizaki et al. [39] utilized Shirasu Porous Glass (SPG) nano-porous membranes to generate NBs. The SPG membrane, developed by SPG Corporation in Japan in

1981, is an inorganic membrane with uniform and adjustable micropore sizes. In their experimental setup, compressed air was introduced into a solution of sodium dodecyl sulfate with concentrations from 0.05 to 0.5 w%. The solution underwent filtration through an SPG membrane with a transmembrane/bubble point pressure ratio of 1.1–2.0. Consistently monodisperse MNBs were prepared, with diameters from 360 to 720 nm. The resulting NBs had an average diameter 8.6 times larger than that of the membrane pore, and their size remained relatively unaffected by air velocity or liquid surface tension. Consequently, the size of the NBs could be effectively manipulated by changing the pore size of the membrane.

Zhang et al. [30] introduced a membrane-based physical sieving approach for producing controllable-sized NBs. The objective of this technique is to regulate the size distribution of the produced NBs through the manipulation of the gas filtration rate and the characteristics of the membrane. Experimental sieving of NBs was carried out using three types of membranes, revealing that the membrane not only had the capability to break down larger bubbles into smaller ones but also facilitated the merging of small bubbles into larger ones during the filtration of bulk nanobubbles (BNBs).

3.3.4. Acoustic Cavitation Method

The acoustic cavitation technique involves inducing localized negative pressure in the liquid through either high-speed propeller rotation or generating negative pressure half-cycles using intense sound waves. This process leads to the formation of micro- and nano-scale bubbles near small gas nuclei [31]. In their experiments on NB generation using the acoustic cavitation method, Nirmalkar et al. [32] revealed the presence of NBs in pure water but not in organic solvents. The disappearance of NBs occurred at a specific ratio of organic solvent to water. This occurrence is ascribed to the electrostatic charge on the NBs' surface, which stabilizes them through the adsorption of hydroxyl ions produced via water's autoionization. In contrast, pure organic solvents lack autoionization.

3.3.5. Microfluidic Method

In the microfluidics method, control over the flow of a combined gas and liquid is achieved using microfluidic chips [33]. A mixture of gases is introduced through a gas inlet, and as it moves through the liquid phase, it experiences viscous forces from the liquid, leading to the generation of MBs. Within these MBs, a portion of the gas dissolves into the aqueous phase and subsequently contracts, giving rise to the formation of non-spherical bubbles (NBs).

This approach involves utilizing a gas mixture containing water-soluble nitrogen and water-insoluble perfluorocarbon (PFC) as the gaseous component in the microfluidic bubble generator. Initially, monodisperse MBs are generated, and as the water-soluble nitrogen dissolves, these microbubbles gradually contract, ultimately forming NBs of a specific size. The degree of bubble contraction can be finely tuned by adjusting the ratio of water-soluble nitrogen to water-insoluble PFC. A notable advantage of this approach lies in its precise control over the size and uniformity of the resulting nanobubbles [40].

3.3.6. Hydrodynamic Cavitation Method

The hydrodynamic cavitation technique involves inducing cavitation in a medium by modifying the flow velocity, leading to pressure fluctuations, similar to the effects achieved through acoustic cavitation methods [34]. Consequently, hydrodynamic cavitation can serve as an alternative to acoustic cavitation for NB generation. Alam et al. [41] performed an investigation on NB generation through hydrodynamic cavitation. The outcomes indicated the successful production of NBs with diameters below 200 nm, and these nanobubbles displayed a negative charge in water. In another study, Wu et al. [42] optimized the cavitation reactor by using numerical simulation to analyze the influence of different geometric parameters on the flow field structure. They determined the most effective design and built a laboratory-scale MNB generator with a vortex-type configuration.

3.4. Application of Nanobubbles in Wastewater Treatment

NBs have proven to be highly useful in wastewater treatment, especially in key processes, including enhanced oxidation, flotation, disinfection, and aeration. Table 4 provides an overview of the uses of NBs in wastewater treatment technologies. These bubble-based technologies have been extensively studied to enhance pollutant removal efficiency while concurrently achieving goals such as facility downsizing, reduced operation time, and lowered operation and maintenance costs for water treatment plants [43].

NBs delivering gases such as air, oxygen, nitrogen, and ozone have been employed for decomposing different compounds. In aerobic biodegradation processes, the use of small-sized NBs proves effective in delivering oxygen to inaccessible regions, enhancing the aerobic biodegradation of substances such as phenanthrene, as demonstrated with saponin-based MNB suspensions [44,45]. Additionally, both aerobic and anaerobic reactor microbial activity can be boosted through the application of air and nitrogen NBs in submerged membrane bioreactors. Furthermore, the catalyzation of chemical reactions and the improvement in detoxification in chemical treatment processes have been achieved using NBs [45]. These advancements contribute to the overall efficiency and sustainability of water and wastewater treatment methodologies. Sections 3.4.1–3.4.4 review the application of NBs in floatation, aeration, and ozone oxidation as well as membrane technology.

Table 4. Application of nanobubbles in wastewater treatment technologies.

Application	Research Focus	Results and Achievements	References
Aeration	Investigation of NB effects on aeration	Improved oxygen transfer efficiency, enhanced DO content, and accelerated pollutant removal.	[46]
Floatation	Evaluation of NB impacts on froth flotation	Reduction in bubble rising velocity; improved froth flotation conditions for coarse particles.	[47]
Membrane technology	Application of NBs in membrane processes	Improved permeability, reduced fouling, and enhanced efficiency in various membrane technologies.	[48]
Ozone oxidation	Use of NBs in ozone treatment	Increased stability, generation of hydroxyl radicals (OH), and improved oxidative efficiency.	[49]

3.4.1. Nanobubbles in Flotation Technology

Flotation is commonly recognized as the most consistent and feasible separation technique for eliminating suspensions containing FOG combined with low-density organic suspended solids and colloids [50]. This separation method operates on the adsorption of gas bubbles, as they rise, onto the surface of finely suspended particles. The adsorption reduces the specific gravity of the particles, causing contaminants to ascend to the surface and boosting their up-flow velocity [51]. This technique is frequently employed to separate extremely fine particles from the solution that lack a significant settling rate.

DAF and induced air flotation (IAF) stand out as widely available flotation techniques. DAF involves the creation of bubbles by reducing the pressure of water already saturated with air above atmospheric pressure [52]. Conversely, IAF relies on mechanical means to generate bubbles, combining a high-speed mechanical agitator with an air injection system [53,54]. Other commercial separation techniques based on flotation include electro-flotation, nozzle flotation, column flotation, centrifugal flotation, jet flotation, and cavitation air flotation.

The study conducted by Lee et al. [55] proved the effective removal of micro-sized oils (less than 20 μm), which may not be efficiently eliminated with ordinary bubbles, through the integration of DAF coupled with a selectively adjustable NB slit nozzle (ranging from

1 to 100 μm). The suspended solids containing oil contaminants were eliminated at a remarkable rate of 95% for COD with a simultaneous 95% recovery. Xiao et al. [56] conducted a study to explore the role of NBs in wastewater treatment, specifically targeting the precipitation of styryl phosphoric acid lead particles and the recovery of organic phosphine. The research revealed that NBs played a crucial role in inhibiting the crystallization of styryl phosphoric acid lead precipitation, resulting in a sediment flotation recovery of less than 20%. However, upon completion of the crystallization process, the precipitated particles experienced flocculation facilitated by NBs, leading to a substantial improvement in flotation recovery, reaching 90%.

Additionally, Etchepare et al. [47] highlighted the significant potential of NBs in wastewater treatment, particularly in achieving high overall oil removal efficiency. The study revealed that combining flocculation with 5 mg/L Dismulgan, followed by flotation with both MBs and NBs at a saturation pressure of 5 bars, resulted in oil removal efficiency exceeding 99%. Furthermore, the study highlighted the ability of NBs to improve overall oil removal efficiency; during the NB conditioning stage following flocculation with 1 mg/L of Dismulgan, an increase in flotation efficiency from 73% to 84% was achieved.

In terms of economic considerations, the expenses associated with coagulation–flocculation using NB flotation technology were found to be more economical compared to conventional methods. The conclusion drawn was that this treatment method proves to be cost-effective for refining wastewater treatment, both chemically and mechanically. This economic efficiency is attributed to the negatively charged nature of NBs in conjunction with the coagulation and flocculation process, especially with the application of Poly Aluminum Chloride as a coagulant [43].

3.4.2. Nanobubbles in Aeration

Aeration is a crucial process in aerobic wastewater treatment, constituting 45–75% of the overall plant energy cost, making it the most substantial portion of the expenses. Effective control of the energy cost is possible by managing DO, a key parameter due to its influence on biological processes [57]. The aeration process is used to biologically treat contaminated water by supplying oxygen to bacteria, facilitating the breakdown of organic substances.

Efficient removal of organic pollutants in wastewater is achievable through traditional activated sludge or the aerated lagoon treatment process. These methods involve aerobic microorganisms with high metabolic kinetics, enabling rapid degradation of organic pollutants in the presence of sufficient oxygen. However, as reported by Huggins et al. [58], sludge disposal and treatment constitute a significant portion (60%) of the total operational cost. The utilization of NBs is, therefore, characterized by a reduction in sludge production and an enhancement in oxygen transfer efficiency within sequencing batch reactor systems. This is accomplished by boosting the number of active bacteria within the floc mass, resulting in a faster and more intense breakdown of organic compounds when compared to aeration with ordinary bubbles.

Air NBs have demonstrated notable effectiveness in treating both domestic and industrial wastewater from diverse origins. For example, Leyva and Flores [59] treated wastewater from the sugar sector with air NBs and found a reduction of 79% in total suspended solids (TSSs) and 85% in chemical oxygen demand (COD) in under 90 min. Furthermore, Reyes and Flores [60] reported that the application of air NBs led to a removal efficiency of 66.21% for total coliforms in wastewater.

Wang and Zhang [61] investigated the incorporation of fine bubble aeration into a deep subsurface wastewater infiltration system to assess nitrogen removal and its mechanisms. The combined system effectively treated wastewater, achieving removal percentages of 95.12%, 98.52%, and 99.98% for COD, NH_4^+-N, and total phosphorus; respectively. The incorporation of fine bubble aeration not only improved the nitrogen removal capacity but also minimized the necessity for temperature adaptation in the deep soil infiltration system. Moreover, the reduction in wastewater COD contributed to a lowered demand for infiltration bed depth.

In contrast to traditional bubbles, NBs significantly enhanced both mass transfer and degradation in wastewater treatment. In a study conducted by Yao et al. [62], municipal wastewater was artificially recreated and subjected to treatment in aerobic-activated sludge systems using NBs. The outcomes of this approach were compared with those obtained using conventional bubble aerators. Notably, the rates of COD removal were considerably superior to those achieved with traditional bubbles. Specifically, there was a 2.04-fold increase at an initial COD concentration of 200 mg/L, a 5.9-fold increase at an initial COD concentration of 400 mg/L, and a 3.26-fold increase at an initial COD concentration of 600 mg/L. Furthermore, the investigation conducted by Xiao and Xu [46] underscored the substantial energy-saving potential, amounting to nearly 80%, associated with the utilization of NB aeration.

3.4.3. Physiochemical Treatment with Nanobubbles

NBs have been used in physicochemical wastewater treatment techniques, such as adsorption, membrane filtration, and ion exchange, to enhance the treatment process and obtain high removal efficiencies.

Dayaranthne et al. [63] investigated the use of MNBs on the RO membrane surface to manage scaling development without the need for additional chemicals. Air MNBs demonstrated superior performance as a chemical-free method for inhibiting scale compared to the use of antiscalants. Experimental results showed that, over four days of continuous operation with MNBs, permeate flux reductions were 86.5% and 83.0% with $CaCO_3$ and $CaSO_4$ feed solutions, respectively. Without MNBs, the permeate flux decreased even more, declining to 63.5% with $CaCO_3$ and 55.8% with $CaSO_4$.

In another study by Dayarathne et al. [48], the use of MNBs proved effective in achieving a 100% recovery of permeate flux and enhancing the cleaning in place of RO membranes in an environmentally friendly approach. The outcomes demonstrated a substantial increase in permeate flux by 24.62% and a solute rejection of 0.8%, attributed to the disruption of the layer triggered by MNBs. This approach contributes to cost reduction in the overall process by eliminating the necessity for restarting the process. Furthermore, using air NBs is considered an environmentally sustainable method in ceramic membrane filtration processes. Ghadimkhani et al. [64] demonstrated the successful unclogging of membrane pores by applying air NBs in comprehensive pilot and bench-scale investigations targeting resistance to fouling. The results proved the reinstatement of permeate flux to its original values through the utilization of NBs.

3.4.4. Advance Oxidation with Ozone Nanobubbles

Ozone, a potent disinfectant widely used in water treatment, exhibits efficacy by binding to bacterial cell walls, rendering them inactive. Despite its capabilities in decomposing organic compounds and inactivating microorganisms, the broader utilization of ozone is constrained by challenges such as low mass transfer efficiency, limited saturation solubility, and a short half-life. These constraints often result in reduced reaction efficiency and underutilization of ozone in water treatment [65]. To address these limitations, the application of NB technology has been explored to enhance the ozonation process in water treatment [14,66]. Leveraging their substantial surface area, rapid mass transfer rates, and prolonged stability in water, NBs contribute to bolstering ozone stability, thereby significantly improving the overall efficiency of the ozonation process.

In the context of wastewater treatment, ozone MNBs have proven effective in addressing both real and synthetic wastewater contaminated with organic pollutants, showcasing notable efficacy across bubble sizes ranging from 20 μm to 1000 nm. Xia and Hu [67] reported that the aeration of ozone NBs successfully reduced sludge organic compounds, resulting in a decrease in mixed liquor-suspended solids (MLSSs) from 53.5% to 31.4% and a decline in oil content from 77.5% to 51.7%. However, this reduction was accompanied by an increase in chemical oxygen demand (COD) by approximately 221% and NH_4^+ by 26%. The incorporation of MBs and catalysts in the process offers a potential cost reduction in sludge management. The treatment efficacy was influenced by pH, with maximum efficiency observed at pH = 5. Under these conditions, the COD removal rate exceeded 63% after 14 h. Additionally, Menendez and Flores [68] treated hospital wastewater containing organic contaminants with ozone–air MNBs, resulting in a substantial decrease in the initial concentrations of the samples and high COD efficiency (92.51% for the first sample and 87.9% for the second sample).

Compared to traditional ozone techniques, the utilization of ozone NBs has demonstrated enhanced efficiency, varying from 1.3 to 19 times, in terms of volumetric ozone gas mass transfer across the gas–liquid interface as reported by Achar et al. [49]. Additionally, the oxidation process was found to be more rapid at pH = 6 compared to pH = 7, emphasizing the significance of pH control [49]. Another study by Jabesa and Ghosh [69] corroborated the effectiveness of employing high ozone generation rates and elevated pH levels in conjunction with ozone NBs in a pilot plant system for the removal of highly water-soluble and toxic diethyl phthalate.

MNBs have demonstrated superior performance compared to macrobubbles, highlighting the effectiveness of smaller-sized bubbles in wastewater treatment processes. A study conducted by Zheng et al. [70] involved the comparison of ozonation using MNBs and macrobubbles for treating wastewater from acrylic fiber manufacturing. The results highlighted that MNBs enhanced the removal of organic compounds, facilitating improved ozonation and biodegradability by accelerating the degradation of alkanes, aromatic compounds, and biorefractory organic compounds. In the MNB ozonation process, the removal efficiencies for COD, NH_3-N, and UV-254 in wastewater were 42%, 21%, and 42%, respectively. Notably, these rates surpassed those achieved by macrobubble ozonation by 25%, 9%, and 35%, respectively, at an equivalent ozone dose of 5 g/h.

In a separate investigation by Chu et al. [71] involving textile wastewater, a comparison was made between the MB system and a bubble contractor. The findings revealed that the MB system exhibited a faster decolorization rate, with a 20% higher removal efficiency of COD compared to the bubble contactor. Additionally, the MB system achieved very high ozone utilization, as evidenced by a significantly lower concentration of off-gas ozone compared to the bubble contactor. When comparing the time required for 80% removal of color, the ozone MB system demonstrated a shorter duration of 140 min compared to the conventional bubbles, which took 280 min.

From previous research, it is evident that ozone MNBs prove highly effective in pollutant reduction, disinfection, and enhancing biodegradability in wastewater treatment. The reduction in bubble size contributes to an improved treatment process by allowing for higher ozone inlet concentrations and better ozone utilization. However, the optimal ozonation rate is contingent on various factors, including process conditions, the nature of pollutants, and the source of wastewater.

3.5. Degradation Mechanism of Pollutants by Nanobubbles

The primary mechanism for removing pollutants from wastewater by the NB-based AOP involves the generation of reactive oxygen species (ROS), such as hydroxyl radicals (OH-) and superoxide radicals (O_2^-). These ROS are generated at the NB–water interface. When NBs collapse, they release significant energy that leads to the formation of ROS [72]. The ROS attack the pollutants, leading to their degradation. Hydroxyl radicals are identified as the most effective ROS in this process. The mechanisms of degradation involve the adsorption of pollutants onto the NB surface, followed by their oxidation through the ROS. This process is facilitated by the collapse of NBs, which generates localized high temperatures and pressures, enhancing the formation of ROS [72,73].

Since NBs produce OH- radicals and generate shear stress, enabling them to degrade pollutants and sterilize bacteria, NB technology can be used to remove organic pollutants and microorganisms from PSW. In PSW treatment processes, NBs can be used in flotation to eliminate SS due to their strong adsorption capability, in biological and aerobic treatment to enhance DO levels and biological activity because of their high mass transfer efficiency, and in AOPs to degrade organic pollutants.

3.6. Factors Affecting Pollutant Removal by Nanobubbles

The efficiency of pollutant removal by NBs can be influenced by a range of factors. These include the pH level, the temperature, the initial concentration of pollutants, as well as the salinity and ions in PSW. Each of these variables can significantly impact the overall removal efficiency [74].

(1) Effect of pH: The degradation of organic pollutants by NBs is influenced by pH levels. Research indicates that acidic conditions enhance the degradation of certain pollutants by NBs, while other studies suggest that an alkaline environment is more effective for different pollutants [73]. For example, NBs best degrade methyl orange, phenol, and rhodamine B under acidic conditions [75]. Conversely, pollutants such as alachlor, benzothiophene, and diethyl phthalate are more effectively degraded by NBs in alkaline conditions [75,76]. This variation is due to the impact of pH on the free radicals produced by NBs and the physical and chemical properties of the pollutants themselves [72]. Thus, the degradation of organic pollutants by NBs involves the dual influence of these factors, which should be comprehensively considered.
The pH of PSW can fluctuate, potentially impacting the effectiveness of AOPs. The quality and pH of PSW are affected by the quality of water used during slaughtering, the type of operation during wastewater collection, the sampling methods used by the individuals involved, and the specific cleaning and sanitizing procedures of the abattoir [5,77]. The pH of PSW was reported to vary between 4.9 and 8.1 with a mean of 6.5 [73,78]. To evaluate how pH influences the degradation process, a study needs to be conducted with NBs across various pH levels.

(2) Effect of temperature: Temperature also plays a significant role in the generation of ROS species by NBs and conversely affects the degradation of pollutants. Yu et al. [76] found that in an alkaline NB solution, the concentration of ROS species initially increased and then decreased as the temperature rose, displaying a parabolic trend with a peak concentration at 65 °C. This phenomenon was attributed to the combined effects of temperature on oxygen reactivity, diffusion coefficient, and DO concentration, where ROS levels followed the same trend. In another study, Wang et al. [73] investigated the impact of temperature on the degradation of rhodamine B (RhB) using cavitation-induced and rotating jets. Their findings showed that the degradation efficiency of rhodamine B improved as the temperature increased from 20 °C to 40 °C, but decreased when the temperature rose further from 40 °C to 60 °C.
These findings demonstrate that temperature has a dual effect on pollutant removal efficiency by NBs. As the equilibrium vapor pressure increases with temperature, the formation of NBs is promoted, which aids in the generation of OH^- and the degradation of organic matter. However, excessively high temperatures cause water vapor to fill the cavitation bubbles, reducing bubble collapse, which hinders the generation of ·OH and the degradation of organic matter [73].

(3) Effect of initial concentrations of pollutants: Ahmadi et al. [79] assessed the impact of different initial COD concentrations (400.0, 600.0, and 800.0 mg L^{-1}) on removal efficiency in the NB aeration system. They found that the removal efficiency decreased as the pollutants' concentrations (i.e., COD) increased. This decline was attributed to a shortage of DO in the wastewater, which is essential for the oxidation process. Enhancing the oxygen content in the wastewater is crucial. Factors such as the bacterial growth curve, the existing phase, and the sludge volume index (SVI) are highly influential. Similarly, Wang et al. [73] investigated the effect of initial concentrations of RhB (0.1, 1, and 10 mg/L) on their removal efficiency by NBs. The results showed that at a high initial concentration of RhB, the degradation of intermediates (by-products)

may compete for the consumption of ROS with the parent RhB compound, leading to a slower reaction rate.

(4) Effect of salinity and other ions: Various constituents in PSW, such as ions, salinity, hardness, and alkalinity, can pose significant challenges for ROS-based AOPs in degrading organic pollutants from wastewater [79]. Some studies have highlighted the impact of foreign ions on the stability of nanobubbles [80]. However, Wang examined the removal efficiency of RhB in the presence of 300 mg/L of background ions, including Ca^{2+}, Mg^{2+}, HCO_3^-, and Cl^-. Their findings showed that oxygen nanobubbles can achieve a removal efficiency of RhB exceeding 92%, even in the presence of the background ions. They concluded that the background ions have a negligible impact on degradation by oxygen nanobubbles.

4. Conventional Treatment of Poultry Slaughterhouse Wastewater

The choice of technology relies on the characteristics of the wastewater, the existing technology options, and adherence to regulations governing the discharge of wastewater and industrial effluents. Conventional treatment for PSW consists of preliminary, primary, and secondary treatments. After preliminary treatment, several combined treatment approaches are possible, with the most prevalent combination being physicochemical treatment as the primary method, followed by biological treatment as the secondary step.

Anaerobic treatment is commonly employed due to its effectiveness in treating wastewater with elevated organic concentrations. However, achieving complete degradation of organic matter in PSW is not attainable with anaerobic treatment alone. Consequently, it is recommended to not use either anaerobic or aerobic processes as the sole treatment method. Combining anaerobic and aerobic processes is proposed as a strategy to minimize the overall cost compared to relying solely on aerobic processes, which incur high expenses for aeration and sludge disposal due to elevated chemical oxygen demand (COD) levels [77,81].

4.1. Preliminary Treatment

The purpose of preliminary treatment is to remove suspended solids and Fats, Oils, and Grease (FOG) from PSW, protecting wastewater equipment from fouling, clogging, and jamming. In the NB treatment of PSW, it is essential to eliminate suspended solids from the wastewater to avoid damage to the NB generator. Furthermore, proper sizing of the screening equipment is crucial to prevent frequent clogging and blockages of the sieve, which would otherwise necessitate extensive manual efforts for screen cleaning.

The most common unit operations for preliminary treatment include screeners, sieves, and strainers. Therefore, large solids with a 10–30 mm diameter are retained while the wastewater passes through. Other preliminary treatment methods include homogenization, equalization, and flotation, among other systems such as catch basins and settlers [78,82].

Mesh screening, being the most common, has been proven effective. In the study conducted by Rusten et al. [83], pilot-scale mesh rotating belt sieves (RBSs) demonstrated over 40% removal of total suspended solids (TSSs) and 30% removal of chemical oxygen demand (COD) using a 350-micron belt at high sieve rates up to 160 m^3/m^2 h.

4.2. Primary Treatment

After preliminary treatment, it is essential to subject the effluent to additional treatments to eliminate pollutants, including organic compounds and nutrients, which may not have been effectively removed during the preliminary treatment. An effective primary wastewater treatment method is Dissolved Air Flotation (DAF), which proves practical for reducing FOG, total suspended solids (TSSs), and biochemical oxygen demand (BOD) [84]. Table 5 below outlines the advantages and disadvantages of the most used physicochemical treatment methods.

Table 5. Primary wastewater treatment methods.

Treatment Method	Description	Advantages	Disadvantages	References
DAF	Introduction of air to facilitate the separation of FOG and solid materials from wastewater.	75% removal for FOG, BOD, and TSSs.	High operational and maintenance costs.	[82,85]
Chemical Coagulation/flocculation	Addition of chemicals to induce particle aggregation for easier removal.	Effective in treating colloidal and fine particles.	Chemical cost and sludge generation.	[86]
Equalization tanks	Balancing and smoothing flow variations and pollutant concentrations before entering treatment processes.	Reduces shock loads to downstream processes.	Requires additional space and monitoring.	[87]
Primary filtration	Physical filtration of suspended solids using barriers like sand or cloth.	Effective for fine particle removal.	Regular maintenance and clogging issues.	[88]

4.3. Secondary Treatment

Preliminary and primary treatments usually do not achieve complete treatment of PSW to the satisfaction levels specified by regulations. Therefore, secondary treatment is introduced to remove the remaining soluble organic compounds left after primary treatment. In the treatment of PSW, biological treatment serves as a secondary step to decrease the concentration of BOD and other soluble compounds after primary treatment [82]. In contrast to primary treatment, biological treatment utilizes microorganisms to eliminate organic substances from wastewater. Various technologies fall under biological processes, which can be broadly categorized into anaerobic and aerobic treatment methods [1,77,89]. The following section explores both aerobic and anaerobic treatment methods, along with the prospective utilization of NBs in these processes.

4.3.1. Anaerobic Treatment

Anaerobic digestion (AD) is a biological process that occurs in the absence of oxygen, whereby microorganisms break down organic matter, resulting in the production of carbon dioxide (CO_2) and methane (CH_4). AD comprises hydrolysis, acidogenesis, acetogenesis, and methanogenesis stages, where a diverse array of microorganisms, including bacteria and archaea, facilitate the decomposition of complex organic compounds in the absence of oxygen. The degradation process is highly dependent on the activity rates of various bacteria [90]. Within anaerobic treatment, organic compounds undergo breakdown into methane, water, and carbon dioxide through the actions of anaerobic bacteria in an oxygen-deprived environment.

The up-flow anaerobic sludge blanket (UASB) reactor is the most common anaerobic digester for the treatment of PSW. In studies conducted by Musa et al. [91] at various organic loading rates (OLRs), the UASB reactor exhibited effective COD removal, achieving 90% removal at an OLR of 0.4 g/L/d. The removal percentages were sustained at 70%, 65%, and below 50% for OLRs of 3, 10, and 15 g/L/d, respectively.

In a different approach, Loganath and Mazumder [92] employed a hybrid UASB with polypropylene media as surfaces for attached growth, resulting in enhanced removal efficiency for total organic carbon (TOC) and total suspended solids (TSSs). The hybrid UASB achieved remarkable removal rates, with 95% efficiency for TOC at a loading rate of 7 kg TOC/m^3·d and a hydraulic retention time (HRT) of 10 h. Furthermore, removal efficiencies for TOC and TSSs were as high as 96% and 98%, respectively.

Afridi et al. [93] used the UASB to investigate fundamental mass transfer characteristics of anaerobic granules by means of microscopic imaging and analytical monitoring. The study emphasized the importance of granule size selection for optimal reactor performance and biogas production. They found that larger granules and higher organic loading enhance mass transfer and biogas production. Furthermore, biogas production rates for 1.75 mm granules increased with higher initial COD concentrations.

Other commonly used anaerobic digesters include anaerobic filters and the anaerobic baffled reactor (ABR), expanded granular sludge bed (EGSB), sequencing batch reactor (SBR), downflow expanded granular bed reactor (DEGBR), and static granular bed reactor (SGBR). Table 6 summarizes the significant results, advantages, and disadvantages of different anaerobic digesters treating PSW.

Table 6. Achievement of common anaerobic digesters.

Anaerobic Digester	Achievement	Advantages	Disadvantages	References
DEGBR and SGBR	Attained a 95% reduction in BOD5, COD, and FOG on days of optimal performance for both reactors.	The DEGBR consistently exhibited more substantial biogas production compared to the SGBR.	The SGBR required over 50 days to achieve a 95% removal of FOG, while the DEGBR accomplished this in 14 days.	[94]
UASB	Approximately 90% COD removal was achieved at an organic loading rate (OLR) of 0.4 g/L/d, resulting in a biogas production of 5 L/d.	VFA concentration remained low, and HRT of 1 day proved effective in removing more than 70% of COD.	COD removal decreased to less than 50% with an increase in the loading rate to 15 g/L/d.	[91]
SGBR is integrated with a single-stage nitrification–denitrification (SND) bioreactor and an ultrafiltration membrane	Average removal efficiencies of 91% for COD, 51% for orthophosphate, 97% for TSSs, and 52% for TDS were attained over a 52-day period.	ufMMs operated in the dead-end filtration mode demonstrated an additional reduction of 65% for COD and 54% for TSSs on average.	The final effluent did not meet the standards for industrial wastewater for PO_4^{3-} and NH_4^+-N.	[95]
EGSB coupled with a membrane bioreactor (MBR)	Overall system efficiency exceeded 97% for TSSs and COD removal and 97.5% removal efficiency for FOG.	The EGSB's performance was not affected by varied organic loading rates (OLRs), emphasizing its robustness under different conditions.	FOG removal fluctuated and did not show a consistent improvement	[96]

Currently, the application of NBs with AD is being explored by researchers in wastewater [97–101]. Recent studies have demonstrated the creation of NB-infused waters with various gases, serving as additives in AD batch systems. The unique characteristics of NBs, such as enhanced gas solubility and the promotion of electrostatic interactions, can influence the physicochemical properties of liquids [24].

The presence of NBs has shown the potential to improve substrate digestibility by generating reactive oxygen species (ROS), thereby facilitating the oxidation of organic materials [102]. Moreover, NBs, particularly those containing air and oxygen, can induce microaerobic conditions, improving the performance of the AD process by enhancing facultative bacterial activity and the methanogenesis stage [103,104].

In a study conducted by Hou et al. [97], the impact of NBs with nitrogen and NBs with air on a two-stage anaerobic digestion (AD) of food waste was investigated. In the initial stage, both nitrogen NBs and air NBs resulted in greater hydrogen production, demonstrating increases of around 23.7% and 39.9%, respectively, compared to deionized water. In the subsequent stage, nitrogen NBs and air NBs contributed to increased methane production by 15.2% and 24.7%, respectively, compared to deionized water.

4.3.2. Aerobic Treatment

Aerobic digestion utilizes oxygen to decompose organic substances and pollutants, converting them into less environmentally harmful compounds such as methane, carbon dioxide, and water. The oxygen requirements, as well as the duration of this treatment, are influenced by the organic content of PSW. Typically, aerobic digestion is implemented as the final step for nutrient removal when combined with anaerobic treatments for sludge purification. Advantages of aerobic treatment include low odor generation, rapid biological growth, and adaptability to changes in temperature and loading rates without requiring elevated operation temperatures [105].

Instead of relying solely on an aerobic process, research has explored the integration of aerobic and anaerobic methods for wastewater treatment. Svierzoski et al. [106] investigated the treatment of wastewater derived from cattle slaughterhouses in the northern region of Brazil (state of Rondônia). They used a two-stage anoxic–aerobic biological system followed by UV-C disinfection to improve nitrogen and organic matter removal. Through the addition of external COD in the form of ethanol, they achieved a maximum total nitrogen removal of 90% with a load of 0.28 kg·N/m^3/d.

Palomares-Rodríguez et al. [107] provided economic and energy-related justification for combining aerobic and anaerobic treatment. Their proposal demonstrated a 76% reduction in energy requirements and a 30% decrease in environmental impact.

While aerobic processes prove efficient in breaking down organic pollutants in wastewater, the major drawback remains the excessive production and disposal of sludge. However, using NBs provides an alternative by reducing sludge production and improving oxygen transfer efficiency in aerobic systems. This is achieved by increasing the count of active bacteria within the floc mass, resulting in faster and more intense breakdown of organic compounds compared to aeration with fine bubbles.

5. Nanobubble Application Prospect for PSW Treatment

NBs have demonstrated promising outcomes in various wastewater applications such as flotation, aeration/oxidation, membrane processes, and ozone oxidation enhancement. However, no attention has been given to the application of small-sized bubbles in slaughterhouse wastewater treatment. There is a need for further exploration in this area to integrate NBs into PSW treatment methods. This approach has the potential to offer a sustainable and chemical-free treatment method, enhancing energy efficiency in the process. Hence, this systematic review was conducted with the objective of identifying the gap in the NB application in wastewater treatment and proposing the application of NBs in PSW treatment technologies. This section discusses the potential application of NBs in PSW treatment.

Despite the existence of abundant literature on the treatment of PSW and the individual applications of NB technology, this review highlights a significant gap in studies focusing on the integration of NB technology specifically for treating PSW. Consequently, this section provides a concise overview of the current treatment methods and technologies for PSW that could be integrated with NB technology. By doing so, the review seeks to underscore the need for more comprehensive research in this area and to draw attention to the potential benefits of combining NB technology with existing PSW treatment methods, highlighting how this innovative approach could enhance treatment efficiency and effectiveness. Therefore, this overview encourages researchers to investigate and enhance the application of NBs in PSW treatment, aiming to address and close the current knowledge gap.

5.1. Nanobubble Aeration with Enzymes

PSW typically contains substantial amounts of FOG, hindering its effectiveness in biological treatment [1]. The primary issue arises from the excessive presence of fats and greases, leading to various problems. Firstly, these substances can accumulate on the sludge surface, diminishing the transfer rates of solution substrate to biomass and oxygen to aerobic microorganisms. Secondly, they can inhibit sludge activity and the development of filamentous microbes, affecting the sediment of the sludge and causing biomass losses through bioreactor outflows [82]. Hence, a pre-treatment process becomes essential to hydrolyze fats and greases and enhance the efficiency of subsequent biological treatment of PSW.

Enzymes are used in the hydrolysis of fats and greases in wastewater such as PSW. Enzymes function as biocatalysts and have demonstrated efficacy in breaking down and transforming complex triglycerides into simpler free fatty acids (FFAs) [108]. This enzymatic approach enhances the performance of microorganisms in subsequent biological treatment processes, as indicated by Jamie et al. [109]. Eco-flush, a bioremediation agent commercially produced by Ergofito and distributed in South Africa through Mavu Biotechnologies, is a blend of natural components and bacteria. It remains inactive until exposed to a nutrient-rich organic source, such as PSW, which serves as a substrate. Once activated, it primarily generates enzymes for the hydrolysis of FOG [96,110]. The natural ingredients in Eco-flush are sourced from glaucids and essential amino acids, forming potent decomposing agents that stimulate specific bacteria to produce enzymes naturally. These enzymes have the capability to break down the hydrocarbon chains present in FOG.

A research investigation conducted by Mdladla et al. [111] involved the application of the Eco-flush bioremediation agent for pre-treatment, revealing removal percentages ranging from 50 to 96% for TSSs, 30 to 76% for COD, and 48 to 96% for FOG prior to anaerobic treatment with an EGSB reactor. Similarly, Dyosile et al. [112] conducted a study on pre-treating PSW, resulting in the removal of FOG up to 80%, along with TSSs and COD average removal rates of 38% and 56%, respectively, prior to introducing PSW into the anaerobic digester. These studies represent a few of the limited reports on the application of the Eco-flush reagent. The noted efficacy in removal underscores the considerable promise of bioremediation technology as a pre-treatment step for high-fat-content wastewater like PSW.

Aeration is required to induce the production of enzymes necessary for breaking down FOG. The utilization of NBs can enhance the oxygen transfer efficiency of the enzymatic treatment of PSW. This is achieved by increasing the number of active bacteria, resulting in the acceleration and intensification of hydrolysis of fats and greases in wastewater.

5.2. Nanobubble Aeration with Ozone

The efficiency of ozone in treating wastewater contaminated with organic compounds is constrained by its slow dissolution rate and rapid decomposition in the aqueous phase. NBs present a novel approach to extend the reactivity of ozone in the aqueous phase, thereby expediting the treatment of contaminants. Nano ozone bubbles, as discussed earlier in this review, exhibit longer lifespans and higher specific areas compared to ordinary bubbles. This characteristic enables them to efficiently eradicate pathogens, highlighting the significant potential for the treatment of wastewater such as PSW. The treatment efficiency of ozone NBs requires investigation. It is hypothesized that ozone NBs, with their remediation efficiency of organic compound-contaminated wastewater, will present impressive or significant results in treating PSW.

5.3. Aerobic Treatment of PSW with Nanobubbles

In aerobic systems, aerobic bacteria are responsible for removing organic materials in the presence of oxygen. Aerobic treatment is typically employed for final decontamination and nutrient removal following physicochemical or anaerobic methods [76]. Common configurations for aerobic treatment of PSW include activated sludge (AS), rotating biological contactor (RBC), aerobic sequencing batch reactor (SBR), and moving bed biofilm reactor (MBBR) processes. These aerobic systems have been widely used for the treatment of PSW due to their simplicity of operation and excellent pollutant removal efficiencies [57]. For instance, Koide et al. [113] found that ASBR, operating in 6 h cycles, achieved removal efficiencies of 95% for COD, 98% for TP, and 97% for TN. Similarly, Oktafani et al. [74]

investigated the effect of aeration on chicken slaughterhouses to assess organic compound removal using the Granular Activated Sludge-Sequencing Batch Reactor (GAS-SBR) system. Their findings showed that after 2 h of aeration, the removal of COD, and BOD was 72.8%. Extending the aeration period to 4 h resulted in a total ammonia removal of 65.8%.

However, the production of sludge and the high energy requirements for aeration make their operation costly and less viable [58]. Therefore, these aerobic systems could be integrated with NB technology for the treatment of PSW to reduce the sludge production and high energy requirement for aeration. As discussed in Section 3.4.2, NBs enhance wastewater aeration by significantly improving oxygen transfer efficiency due to their high surface area-to-volume ratio and prolonged stability in water.

6. Conclusions

This review has highlighted the efficacy of NB technology in wastewater treatment, capitalizing on distinctive bubble characteristics such as small size, slow rising velocity, negatively charged ZP, stability, and the ability to generate free radicals. NB applications in wastewater treatment demonstrate heightened mass transfer rates, facilitating efficient treatment with air, oxygen, and ozone. Numerous studies across different wastewater sources validate the enhanced mass transfer achieved through stabilized small-sized bubbles, which have been proven successful in removing a spectrum of contaminants in wastewater.

Various anaerobic digesters, such as UASB and SGBR, demonstrated COD removal rates of up to 97% when treating slaughterhouse wastewater. Similarly, aerobic processes achieved 90% removal of total nitrogen. Moreover, combining anaerobic and aerobic treatment methods led to a 76% reduction in energy consumption. NBs proved effective in removing COD and other pollutants from wastewater. For example, when applied in flotation, aeration, and advanced oxidation, NBs achieved up to 95%, 85%, and 92.5% COD removal, respectively.

Although NBs have demonstrated remarkable results, some wastewater, like PSW, necessitate further investigation into their treatment using NB technology. NBs could potentially be applied with enzymes, ozone, or aeration for enhanced PSW treatment. These treatment methods require further investigation to study their efficacy. Furthermore, NBs present an environmentally friendly approach to wastewater treatment through the generation of free radicals, offering potential replacements for current expensive treatment processes. A comprehensive examination of related costs and energy consumption is essential for a thorough understanding of the wastewater treatment process.

Overall, the trends in this review indicate a shift towards advancing our understanding of nanobubble technology and its practical applications in water treatment and industrial processes. Key guiding values include efficiency, sustainability, and scalability, with an emphasis on harnessing nanobubble technology to address pressing environmental and resource management challenges.

7. Recommendations and Perspectives for Future Studies

Based on the conclusions drawn and the information provided in the literature, the following suggestions for future research are proposed:

(1) Exploration of novel applications: This review highlighted the effectiveness of NB technology in various wastewater treatment processes, including flotation, aeration, physicochemical treatment, and ozone oxidation. Future studies can explore novel applications of NBs in treating specific types of wastewater, such as PSW.

(2) Optimization of operating conditions: Research is needed to optimize the operating conditions such as pH, temperature, DO, aeration time, and pollutant levels in PSW on the NB performance in treating PSW. Understanding the influence of these parameters on treatment efficiency and energy consumption can lead to more sustainable and cost-effective treatment solutions for PSW.

(3) Integration with advanced treatment methods: NB technology can be integrated with other advanced treatment methods, such as membrane filtration, floatation, and

advanced oxidation processes. Future studies can investigate the synergistic effects of combining NBs with these techniques to enhance pollutant removal efficiency.

(4) Economic assessments: Future studies should include comprehensive assessments of NB technology compared to conventional treatment methods. Evaluating factors such as energy consumption and chemical usage can help identify the economic benefits of NB-based treatment for PSW.

By addressing these perspectives in future studies and developments, researchers can advance the knowledge and application of NB technology for PSW treatment, ultimately contributing to improved water quality, environmental sustainability, and public health.

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References

1. Bustillo-Lecompte, C.F.; Mehrvar, M. Slaughterhouse wastewater characteristics, treatment, and management in the meat processing industry: A review on trends and advances. *J. Environ. Manag.* **2015**, *161*, 287–302. [CrossRef] [PubMed]
2. Hilares, R.T.; Atoche-Garay, D.F.; Pagaza, D.A.P.; Ahmed, M.A.; Andrade, G.J.C.; Santos, J.C. Promising physicochemical technologies for poultry slaughterhouse wastewater treatment: A critical review. *J. Environ. Chem. Eng.* **2021**, *9*, 105174. [CrossRef]
3. Basitere, M.; Njoya, M.; Rinquest, Z.; Ntwampe, S.K.O.; Sheldon, M.S. Performance evaluation and kinetic parameter analysis for static granular bed reactor (SGBR) for treating poultry slaughterhouse wastewater at mesophilic condition. *Water Pract. Technol.* **2019**, *14*, 259–268. [CrossRef]
4. South African Government. National Water Act 36 of 1998. Available online: https://www.gov.za/documents/national-water-act (accessed on 17 February 2024).
5. Njoya, M.; Basitere, M.; Ntwampe, S.K.O. Analysis of the Characteristics of Poultry Slaughterhouse Wastewater (PSW) and Its Treatability. *Water Pract. Technol.* **2019**, *14*, 959–970. [CrossRef]
6. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *Int. J. Surg.* **2021**, *88*, 105906. [CrossRef] [PubMed]
7. Agarwal, A.; Ng, W.J.; Liu, Y. Principle and Applications of Microbubble and Nanobubble Technology for Water Treatment. *Chemosphere* **2011**, *84*, 1175–1180. [CrossRef] [PubMed]
8. Rameshkumara, C.; Senthilkumarb, G.; Subalakshmic, R.; Gogoid, R. Generation and characterization of nanobubbles by ionization method for wastewater treatment. *Desalination Water Treat.* **2019**, *164*, 98–101. [CrossRef]
9. Kim, M.S.; Kwak, D.H. Effect of zeta potential on collision attachment coefficient and removal efficiency for dissolved carbon dioxide flotation. *Environ. Eng. Sci.* **2017**, *34*, 272–280. [CrossRef]
10. *ISO 20480-1:2017*; Fine Bubble Technology—General Principles for Usage and Measurement of Fine Bubbles. International Organization for Standardization: Geneva, Switzerland, 2017. Available online: https://www.iso.org/obp/ui/#iso:std:iso:20480:-1:ed-1:v1:en (accessed on 17 February 2024).
11. Gurung, A.; Dahl, O.; Jansson, K. The fundamental phenomena of nanobubbles and their behavior in wastewater treatment technologies. *Geosystem Eng.* **2016**, *19*, 133–142. [CrossRef]
12. Phan, K.K.T.; Truong, T.; Wang, Y.; Bhandari, B. Nanobubbles: Fundamental characteristics and applications in food processing. *Trends Food Sci. Technol.* **2020**, *95*, 118–130. [CrossRef]
13. Sakr, M.; Mohamed, M.M.; Maraqa, M.A.; Hamouda, M.A.; Hassan, A.A.; Ali, J.; Jung, J. A critical review of the recent developments in micro–nano bubbles applications for domestic and industrial wastewater treatment. *Alex. Eng. J.* **2022**, *61*, 6591–6612. [CrossRef]
14. Shangguan, Y.; Yu, S.; Gong, C.; Wang, Y.; Yang, W.; Hou, L. A review of Microbubble and its applications in ozonation. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *128*, 012149. [CrossRef]
15. Bui, T.T.; Nguyen, D.C.; Han, M. Average size and zeta potential of nanobubbles in different reagent solutions. *J. Nanoparticle Res.* **2019**, *21*, 173. [CrossRef]

16. Meegoda, J.N.; Aluthgun Hewage, S.; Batagoda, J.H. Stability of nanobubbles. *Environ. Eng. Sci.* **2018**, *35*, 1216–1227. [CrossRef]
17. Takahashi, M.; Chiba, K.; Li, P. Free-radical generation from collapsing microbubbles in the absence of a dynamic stimulus. *J. Phys. Chem. B* **2007**, *111*, 1343–1347. [CrossRef] [PubMed]
18. Serizawa, A. Fundamentals and applications of micro/nano bubbles. In Proceedings of the 1st International Symposium on Application of High voltage, Plasmas & Micro/Nano Bubbles to Agriculture and Aquaculture, Chiang Mai, Thailand, 5–6 January 2017.
19. Xiong, X.; Wang, B.; Zhu, W.; Tian, K.; Zhang, H. A review on ultrasonic catalytic microbubbles ozonation processes: Properties, hydroxyl radicals generation pathway and potential in application. *Catalysts* **2018**, *9*, 10. [CrossRef]
20. Zhang, M.; Qiu, L.; Liu, G. Basic characteristics and application of micro-nano Bubbles in water treatment. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *510*, 042050. [CrossRef]
21. Masuda, N.; Maruyama, A.; Eguchi, T.; Hirakawa, T.; Murakami, Y. Influence of microbubbles on free radical generation by ultrasound in aqueous solution: Dependence of ultrasound frequency. *J. Phys. Chem. B* **2015**, *119*, 12887–12893. [CrossRef] [PubMed]
22. Li, H.; Hu, L.; Song, D.; Al-Tabbaa, A. Subsurface transport behavior of Micro-Nano bubbles and potential applications for groundwater remediation. *Int. J. Environ. Res. Public Health* **2013**, *11*, 473–486. [CrossRef]
23. Li, H.; Hu, L.; Song, D.; Lin, F. Characteristics of micro-nano bubbles and potential application in groundwater bioremediation. *Water Environ. Res.* **2014**, *86*, 844–851. [CrossRef]
24. Atkinson, A.J.; Apul, O.G.; Schneider, O.; Garcia-Segura, S.; Westerhoff, P. Nanobubble technologies offer opportunities to improve water treatment. *Acc. Chem. Res.* **2019**, *52*, 1196–1205. [CrossRef] [PubMed]
25. Liu, C.; Tang, Y. Application research of micro and nano bubbles in Water Pollution Control. *E3S Web Conf.* **2019**, *136*, 06028. [CrossRef]
26. Azevedo, A.; Oliveira, H.; Rubio, J. Bulk nanobubbles in the mineral and environmental areas: Updating research and applications. *Adv. Colloid Interface Sci.* **2019**, *271*, 101992. [CrossRef] [PubMed]
27. Senthilkumar, G.; Purusothaman, M.; Rameshkumar, C.; Joy, N.; Sachin, S.; Siva Thanigai, K. Generation and characterization of nanobubbles for heat transfer applications. *Mater. Today Proc.* **2021**, *43*, 3391–3393. [CrossRef]
28. Li, J.; Song, Y.; Yin, J.; Wang, D. Investigation on the effect of geometrical parameters on the performance of a venturi type bubble generator. *Nucl. Eng. Des.* **2017**, *325*, 90–96. [CrossRef]
29. Zhao, L.; Mo, Z.; Sun, L.; Xie, G.; Liu, H.; Du, M.; Tang, J. A visualized study of the motion of individual bubbles in a venturi-type bubble generator. *Prog. Nucl. Energy* **2017**, *97*, 74–89. [CrossRef]
30. Zhang, R.; Gao, Y.; Chen, L.; Ge, G. Controllable preparation of monodisperse nanobubbles by membrane sieving. *Colloids Surf. A Physicochem. Eng. Asp.* **2022**, *642*, 128656. [CrossRef]
31. Ferrari, A. Fluid dynamics of acoustic and hydrodynamic cavitation in hydraulic power systems. *Proc. R. Soc. A Math. Phys. Eng. Sci.* **2017**, *473*, 20160345. [CrossRef] [PubMed]
32. Nirmalkar, N.; Pacek, A.W.; Barigou, M. Bulk nanobubbles from acoustically cavitated aqueous organic solvent mixtures. *Langmuir* **2019**, *35*, 2188–2195. [CrossRef]
33. Yi-Qiang, F.; Hong-Liang, W.; Ke-Xin, G.; Jing-Ji, L.I.U.; Dong-Ping, C.H.A.I.; Zhang, Y.J. Applications of modular microfluidics technology. *Chin. J. Anal. Chem.* **2018**, *46*, 1863–1871.
34. Zheng, H.; Zheng, Y.; Zhu, J. Recent developments in hydrodynamic cavitation reactors: Cavitation mechanism, reactor design, and applications. *Engineering* **2022**, *19*, 180–198. [CrossRef]
35. Etchepare, R.; Oliveira, H.; Nicknig, M.; Azevedo, A.; Rubio, J. Nanobubbles: Generation using a multiphase pump, properties and features in flotation. *Min. Eng.* **2017**, *112*, 19–26. [CrossRef]
36. Parmar, R.; Majumder, S.K. Microbubble generation and Microbubble-aided transport process intensification—A state-of-the-art report. *Chem. Eng. Process. Process Intensif.* **2013**, *64*, 79–97. [CrossRef]
37. Huang, J.; Sun, L.; Du, M.; Liang, Z.; Mo, Z.; Tang, J.; Xie, G. An investigation on the performance of a micro-scale Venturi Bubble Generator. *Chem. Eng. J.* **2020**, *386*, 120980. [CrossRef]
38. Ulatowski, K.; Sobieszuk, P. Gas nanobubble dispersions as the important agent in Environmental Processes–Generation Methods Review. *Water Environ. J.* **2020**, *34*, 772–790. [CrossRef]
39. Kukizaki, M.; Goto, M. Size control of nanobubbles generated from Shirasu-porous-glass (SPG) membranes. *J. Membr. Sci.* **2006**, *281*, 386–396. [CrossRef]
40. Xu, J.; Salari, A.; Wang, Y.; He, X.; Kerr, L.; Darbandi, A.; de Leon, A.C.; Exner, A.A.; Kolios, M.C.; Yuen, D.; et al. Microfluidic generation of monodisperse nanobubbles by selective gas dissolution. *Small* **2021**, *17*, 2100345. [CrossRef]
41. Alam, H.S.; Sutikno, P.; Soelaiman, T.A.; Sugiarto, A.T. Bulk nanobubbles: Generation using a two-chamber swirling flow nozzle and long-term stability in water. *J. Flow Chem.* **2021**, *12*, 161–173. [CrossRef]
42. Wu, M.; Song, H.; Liang, X.; Huang, N.; Li, X. Generation of micro-nano bubbles by self-developed Swirl-Type micro-nano Bubble generator. *Chem. Eng. Process.-Process Intensif.* **2022**, *181*, 109136. [CrossRef]
43. Temesgen, T.; Bui, T.T.; Han, M.; Kim, T.; Park, H. Micro and nanobubble technologies as a new horizon for water-treatment techniques: A Review. *Adv. Colloid Interface Sci.* **2017**, *246*, 40–51. [CrossRef]
44. Khuntia, S.; Majumder, S.K.; Ghosh, P. Microbubble-aided water and wastewater purification: A Review. *Rev. Chem. Eng.* **2012**, *28*, 191–221. [CrossRef]

45. Kaushik, G.; Chel, A. Microbubble technology: Emerging field for water treatment. *Bubble Sci. Eng. Technol.* **2014**, *5*, 33–38. [CrossRef]
46. Xiao, W.; Xu, G. Mass transfer of nanobubble aeration and its effect on biofilm growth: Microbial Activity and Structural Properties. *Sci. Total Environ.* **2020**, *703*, 134976. [CrossRef]
47. Etchepare, R.; Oliveira, H.; Azevedo, A.; Rubio, J. Separation of emulsified crude oil in saline water by dissolved air flotation with Micro and nanobubbles. *Sep. Purif. Technol.* **2017**, *186*, 326–332. [CrossRef]
48. Dayarathne, H.N.P.; Choi, J.; Jang, A. Enhancement of cleaning-in-place (CIP) of a reverse osmosis desalination process with air micro-nano bubbles. *Desalination* **2017**, *422*, 1–4. [CrossRef]
49. Achar, J.C.; Nam, G.; Jung, J.; Klammler, H.; Mohamed, M.M. Microbubble ozonation of the antioxidant butylated hydroxytoluene: Degradation kinetics and toxicity reduction. *Environ. Res.* **2020**, *186*, 109496. [CrossRef]
50. Kim, M.S.; Han, M.; Kim, T.I.; Lee, J.W.; Kwak, D.H. Effect of nanobubbles for improvement of water quality in freshwater: Flotation model simulation. *Sep. Purif. Technol.* **2020**, *241*, 116731. [CrossRef]
51. Nazari, S.; Shafaei, S.Z.; Shahbazi, B.; Chehreh Chelgani, S. Study relationships between flotation variables and recovery of coarse particles in the absence and presence of nanobubble. *Colloids Surf. A Physicochem. Eng. Asp.* **2018**, *559*, 284–288. [CrossRef]
52. Fonseca, R.R.; Thompson, J.P.; Franco, I.C.; da Silva, F.V. Automation and control of a dissolved air flotation pilot plant. *IFACPapersOnLine* **2017**, *50*, 3911–3916. [CrossRef]
53. Saththasivam, J.; Loganathan, K.; Sarp, S. An overview of oil–water separation using gas flotation systems. *Chemosphere* **2016**, *144*, 671–680. [CrossRef]
54. Prakash, R.; Majumder, S.K.; Singh, A. Flotation technique: Its mechanisms and design parameters. *Chem. Eng. Process* **2018**, *127*, 249–270. [CrossRef]
55. Lee, J.; Cho, W.C.; Poo, K.M.; Choi, S.; Kim, T.N.; Son, E.B.; Choi, Y.J.; Kim, Y.M.; Chae, K.J. Refractory oil wastewater treatment by dissolved air flotation, electrochemical advanced oxidation process, and magnetic biochar integrated system. *J. Water Process Eng.* **2020**, *36*, 101358. [CrossRef]
56. Xiao, W.; Ke, S.; Quan, N.; Zhou, L.; Wang, J.; Zhang, L.; Dong, Y.; Qin, W.; Qiu, G.; Hu, J. The role of nanobubbles in the precipitation and recovery of organic-phosphine-containing beneficiation wastewater. *Langmuir* **2018**, *34*, 6217–6224. [CrossRef] [PubMed]
57. Drewnowski, J.; Remiszewska-Skwarek, A.; Duda, S.; Łagód, G. Aeration process in bioreactors as the main energy consumer in a wastewater treatment plant. Review of solutions and methods of process optimization. *Processes* **2019**, *7*, 311. [CrossRef]
58. Huggins, T.; Fallgren, P.H.; Jin, S.; Ren, Z.J. Energy and performance comparison of microbial fuel cell and conventional aeration treating of wastewater. *J. Microb. Biochem. Technol.* **2013**, *S6*, 2. [CrossRef]
59. Leyva, M.; Valverde Flores, J. Reduction of COD and TSS of waste effluents from a sugar industry through the use of air micro-nanobubbles. *J. Nanotechnol.* **2018**, *2*, 7. [CrossRef]
60. Reyes, R.; Valverde Flores, J. Efficiency Of Micro-Nanobubbles for Wastewater Treatment in Puerto Bermúdez, Oxapampa, Pasco. *J. Nanotechnol.* **2017**, *1*, 18–24. [CrossRef]
61. Wang, H.; Zhang, L. Research on the nitrogen removal efficiency and mechanism of deep subsurface wastewater infiltration systems by fine bubble aeration. *Ecol. Eng.* **2017**, *107*, 33–40. [CrossRef]
62. Yao, K.; Chi, Y.; Wang, F.; Yan, J.; Ni, M.; Cen, K. The effect of microbubbles on gas-liquid mass transfer coefficient and degradation rate of cod in wastewater treatment. *Water Sci. Technol.* **2016**, *73*, 1969–1977. [CrossRef]
63. Dayarathne, H.N.P.; Jeong, S.; Jang, A. Chemical-free scale inhibition method for seawater reverse osmosis membrane process: Air micro-nano bubbles. *Desalination* **2019**, *461*, 1–9. [CrossRef]
64. Ghadimkhani, A.; Zhang, W.; Marhaba, T. Ceramic membrane defouling (cleaning) by Air Nano bubbles. *Chemosphere* **2016**, *146*, 379–384. [CrossRef] [PubMed]
65. Hung, I. Ultrafine Bubble-Enhanced Ozonation for Water Treatment. Master's Thesis, The University of Arizona, Tucson, AZ, USA, 2016.
66. Andinet, T.; Kim, I.; Lee, J.Y. Effect of microbubble generator operating parameters on oxygen transfer efficiency in water. *Desalination Water Treat.* **2016**, *57*, 26327–26335. [CrossRef]
67. Xia, Z.; Hu, L. Treatment of organics contaminated wastewater by ozone micro-nano-bubbles. *Water* **2018**, *11*, 55. [CrossRef]
68. Menendez, D.; Valverde Flores, J. Reduction of hospital wastewater through ozone-air micro-nanobubbles. *J. Nanotechnol.* **2018**, *1*, 59. [CrossRef]
69. Jabesa, A.; Ghosh, P. Removal of diethyl phthalate from water by ozone microbubbles in a pilot plant. *J. Environ. Manag.* **2016**, *180*, 476–484. [CrossRef] [PubMed]
70. Zheng, T.; Wang, Q.; Zhang, T.; Shi, Z.; Tian, Y.; Shi, S.; Smale, N.; Wang, J. Microbubble enhanced ozonation process for advanced treatment of wastewater produced in acrylic fiber manufacturing industry. *J. Hazard. Mater.* **2015**, *287*, 412–420. [CrossRef] [PubMed]
71. Chu, L.B.; Xing, X.H.; Yu, A.F.; Sun, X.L.; Jurcik, B. Enhanced treatment of practical textile wastewater by microbubble ozonation. *Process Saf. Environ. Prot.* **2008**, *86*, 389–393. [CrossRef]
72. Wang, B.; Wang, L.; Cen, W.; Lyu, T.; Jarvis, P.; Zhang, Y.; Zhang, Y.; Han, Y.; Wang, L.; Pan, G.; et al. Exploring a chemical input free advanced oxidation process based on nanobubble technology to treat organic micropollutants. *Environ. Pollut.* **2024**, *340*, 122877. [CrossRef]

73. Wang, T.; Yang, C.; Sun, P.; Wang, M.; Lin, F.; Fiallos, M.; Khu, S.T. Generation Mechanism of Hydroxyl Free Radicals in Micro–Nanobubbles Water and Its Prospect in Drinking Water. *Processes* **2024**, *12*, 683. [CrossRef]
74. Oktafani, B.; Siami, L.; Hadisoebroto, R.; Tazkiaturrizki, T.; Ratnaningsih, R. The effect of aeration time on chicken slaughterhouse water treatment using gas-SBR. *J. Phys. Conf. Ser.* **2019**, *1402*, 033011. [CrossRef]
75. Khuntia, S.; Majumder, S.K.; Ghosh, P. Quantitative prediction of generation of hydroxyl radicals from ozone microbubbles. *Chem. Eng. Res. Des.* **2015**, *98*, 231–239. [CrossRef]
76. Yu, X.; Wang, Z.; Lv, Y.; Wang, S.; Zheng, S.; Du, H.; Zhang, Y. Effect of microbubble diameter, alkaline concentration and temperature on reactive oxygen species concentration. *J. Chem. Technol. Biotechnol.* **2017**, *92*, 1738–1745. [CrossRef]
77. Gutu, L.; Basitere, M.; Harding, T.; Ikumi, D.; Njoya, M.; Gaszynski, C. Multi-Integrated Systems for Treatment of Abattoir Wastewater: A Review. *Water* **2021**, *13*, 2462. [CrossRef]
78. Bustillo-Lecompte, C.; Mehrvar, M.; Quiñones-Bolaños, E. Slaughterhouse wastewater characterisation and treatment: An economic and public health necessity of the meat processing industry in Ontario, Canada. *J. Geosci. Environ. Prot.* **2016**, *4*, 175–186.
79. Ahmadi, M.; Doroodmand, M.M.; Nabi Bidhendi, G.; Torabian, A.; Mehrdadi, N. Efficient Wastewater Treatment via Aeration Through a Novel Nanobubble System in Sequence Batch Reactors. *Front. Energy Res.* **2022**, *10*, 884353. [CrossRef]
80. Yu, H.; Liu, Y.; Xu, M.; Cong, S.; Liu, M.; Zou, D. Hydroxylamine facilitated heterogeneous fenton-like reaction by nano micro-electrolysis material for rhodamine B degradation. *J. Clean. Prod.* **2021**, *316*, 128136. [CrossRef]
81. Cao, W.; Mehrvar, M. Slaughterhouse wastewater treatment by combined anaerobic baffled reactor and UV/H_2O_2 processes. *Chem. Eng. Res. Des.* **2011**, *89*, 1136–1143. [CrossRef]
82. Musa, M.A.; Idrus, S. Physical and biological treatment technologies of slaughterhouse wastewater: A review. *Sustainability* **2021**, *13*, 4656. [CrossRef]
83. Rusten, B.; Rathnaweera, S.S.; Rismyhr, E.; Sahu, A.K.; Ntiako, J. Rotating belt sieves for primary treatment, chemically enhanced primary treatment and secondary solids separation. *Water Sci. Technol.* **2017**, *75*, 2598–2606. [CrossRef]
84. Bhatia, R.K.; Sakhuja, D.; Mundhe, S.; Walia, A. Renewable Energy Products through Bioremediation of Wastewater. *Sustainability* **2020**, *12*, 7501. [CrossRef]
85. De Nardi, I.R.; Del Nery, V.; Amorim, A.K.B.; Dos Santos, N.G.; Chimenes, F. Performances of SBR, chemical-DAF and UV disinfection for poultry slaughterhouse wastewater reclamation. *Desalination* **2011**, *269*, 184–189. [CrossRef]
86. Teh, C.Y.; Budiman, P.M.; Shak, K.P.Y.; Wu, T.Y. Recent Advancement of Coagulation-Flocculation and Its Application in Wastewater Treatment. *Ind. Eng. Chem. Res.* **2016**, *55*, 4363–4389. [CrossRef]
87. Fotso, S.E. Development of a Dynamic Simulation Model for Equalization Tanks. Master's Thesis, Faculty of Engineering and the Built Environment, University of Cape Town, Western Cape, South Africa, 2021.
88. Gidstedt, S.; Betsholtz, A.; Cimbritz, M.; Davidsson, Å.; Hagman, M.; Karlsson, S.; Takman, M.; Svahn, O.; Micolucci, F. Chemically enhanced primary treatment, microsieving, direct membrane filtration and GAC filtration of municipal wastewater: A pilot-scale study. *Environ. Technol.* **2022**, *45*, 28–39. [CrossRef] [PubMed]
89. Philipp, M.; Masmoudi Jabri, K.; Wellmann, J.; Akrout, H.; Bousselmi, L.; Geißen, S.U. Slaughterhouse Wastewater Treatment: A Review on Recycling and Reuse Possibilities. *Water* **2021**, *13*, 3175. [CrossRef]
90. Aziz, A.; Basheer, F.; Sengar, A.; Irfanullah, A.; Khan, S.U.; Farooqi, I.H. Biological wastewater treatment (anaerobic-aerobic) technologies for safe discharge of treated slaughterhouse and meat processing wastewater. *Sci. Total Environ.* **2019**, *686*, 681–708. [CrossRef] [PubMed]
91. Musa, M.; Idrus, S.; Hasfalina, C.; Daud, N. Effect of Organic Loading Rate on Anaerobic Digestion Performance of Mesophilic (UASB) Reactor Using Cattle SlaughterhouseWastewater as Substrate. *Int. J. Environ. Res. Public Health* **2018**, *15*, 2220. [CrossRef] [PubMed]
92. Loganath, R.; Mazumder, D. Performance study on organic carbon, total nitrogen, suspended solids removal and biogas production in hybrid UASB reactor treating real slaughterhouse wastewater. *J. Environ. Chem. Eng.* **2018**, *6*, 3474–3484. [CrossRef]
93. Afridi, Z.U.R.; Jing, W.; Younas, H. Biogas production and fundamental mass transfer mechanism in anaerobic granular sludge. *Sustainability* **2019**, *11*, 4443. [CrossRef]
94. Njoya, M.; Basitere, M.; Ntwampe, S.K.O.; Lim, J.W. Performance evaluation and kinetic modeling of down-flow high-rateanaerobic bioreactors for poultry slaughterhouse wastewater treatment. *Environ. Sci. Pollut. Res.* **2021**, *28*, 9529–9541. [CrossRef]
95. Rinquest, Z.; Basitere, M.; Ntwampe, S.K.O.; Njoya, M. Poultry slaughterhouse wastewater treatment using a static granular bed reactor coupled with single stage nitrification-denitrification and ultrafiltration systems. *J. Water Process Eng.* **2019**, *29*, 100778. [CrossRef]
96. Meyo, H.B.; Njoya, M.; Basitere, M.; Ntwampe, S.K.O.; Kaskote, E. Treatment of poultry slaughterhouse wastewater (PSW) using a pretreatment stage, an expanded granular sludge bed reactor (EGSB), and a membrane bioreactor (MBR). *Membranes* **2021**, *11*, 345. [CrossRef] [PubMed]
97. Hou, T.; Zhao, J.; Lei, Z.; Shimizu, K.; Zhang, Z. Enhanced energy recovery via separate hydrogen and methane production from two-stage anaerobic digestion of food waste with nanobubble water supplementation. *Sci. Total Environ.* **2021**, *761*, 143234. [CrossRef]
98. Fan, Y.; Lei, Z.; Guo, Z.; Huang, W.; Wang, D.; Wang, X.; Zhang, Z.; Shimizu, K. Enhanced solubilization of solid organics and methane production by anaerobic digestion of swine manure under nano-bubble water addition. *Bioresour. Technol.* **2020**, *299*, 122512. [CrossRef]

99. Fan, Y.; Lei, Z.; Yang, X.; Kobayashi, M.; Adachi, Y.; Zhang, Z.; Shimizu, K. Effect of nano-bubble water on high solid anaerobic digestion of pig manure: Focus on digestion stability, methanogenesis performance and related mechanisms. *Bioresour. Technol.* **2020**, *315*, 123793. [CrossRef] [PubMed]
100. Yang, X.; Nie, J.; Wang, D.; Zhao, Z.; Kobayashi, M.; Adachi, Y.; Shimizu, K.; Lei, Z.; Zhang, Z. Enhanced hydrolysis of waste activated sludge for methane production via anaerobic digestion under N2-nanobubble water addition. *Sci. Total Environ.* **2019**, *693*, 133524. [CrossRef]
101. Yang, X.; Nie, J.; Wei, Y.; Zhao, Z.; Shimizu, K.; Lei, Z.; Zhang, Z. Simultaneous enhancement on lignin degradation and methane production from anaerobic co-digestion of waste activated sludge and alkaline lignin supplemented with N2- nanobubble water. *Bioresour. Technol. Rep.* **2020**, *11*, 100470. [CrossRef]
102. Wang, X.; Lei, Z.; Shimizu, K.; Zhang, Z.; Lee, D.J. Improved methane production from corn straw using anaerobically digested sludge pre-augmented by nanobubble water. *Bioresour. Technol.* **2020**, *311*, 123479. [CrossRef]
103. Nguyen, D.; Khanal, S.K. A little breath of fresh air into an anaerobic system: How microaeration facilitates anaerobic digestion process. *Biotechnol. Adv.* **2018**, *36*, 1971–1983. [CrossRef] [PubMed]
104. Nguyen, D.; Wu, Z.; Shrestha, S.; Lee, P.H.; Raskin, L.; Khanal, S.K. Intermittent micro-aeration: New strategy to control volatile fatty acid accumulation in high organic loading anaerobic digestion. *Water Res.* **2019**, *166*, 115080. [CrossRef]
105. Hamawand, I.; Ghadouani, A.; Bundschuh, J.; Hamawand, S.; Al Juboori, R.A.; Chakrabarty, S.; Yusaf, T. A critical review on processes and energy profile of the Australian Meat Processing Industry. *Energies* **2017**, *10*, 731. [CrossRef]
106. Svierzoski, N.D.S.; Matheus, M.C.; Bassin, J.P.; Brito, Y.D.; Mahler, C.F.; Webler, A.D. Treatment of a slaughterhouse wastewater by anoxic-aerobic biological reactors followed by UV-C disinfection and microalgae bioremediation. *Water Environ. Res.* **2020**, *93*, 409–420. [CrossRef] [PubMed]
107. Palomares-Rodríguez, C.; Martínez-Guido, S.I.; Apolinar-Cortés, J.; del Carmen Chávez-Parga, M.; García-Castillo, C.C.; Ponce-Ortega, J.M. Environmental, technical, and economic evaluation of a new treatment for wastewater from slaughterhouses. *Int. J. Environ. Res.* **2017**, *11*, 535–545. [CrossRef]
108. Affes, M.; Aloui, F.; Hadrich, F.; Loukil, S.; Sayadi, S. Effect of bacterial lipase on anaerobic co-digestion of slaughterhouse wastewater and grease in batch condition and continuous fixed-bed reactor. *Lipids Health Dis.* **2017**, *16*, 195. [CrossRef] [PubMed]
109. Jamie, A.; Alshami, A.S.; Maliabari, Z.O.; Ali Ateih, M.; Al Hamouz, O.C.S. Immobilization and enhanced catalytic activity of lipase on modified MWCNT for oily wastewater treatment. *Environ. Prog. Sustain. Energy* **2016**, *35*, 1441–1449. [CrossRef]
110. Ergofito. Ecoflush Eliminated Ammonia. Ecoflush Eliminated Odours. Available online: https://www.ergofito.co.za/home (accessed on 16 February 2024).
111. Mdladla, C.T.; Dyosile, P.A.; Njoya, M.; Basitere, M.; Ntwampe, S.K.O.; Kaskote, E. Poultry Slaughterhouse Wastewater Remediation Using a Bio-Delipidation Pre-Treatment Unit Coupled with an Expanded Granular Sludge Bed Reactor. *Processes* **2021**, *9*, 1938. [CrossRef]
112. Dyosile, P.A.; Mdladla, C.; Njoya, M.; Basitere, M.; Ntwampe, S.K.O.; Kaskote, E. Assessment of an Integrated and Sustainable Multistage System for the Treatment of Poultry Slaughterhouse Wastewater. *Membranes* **2021**, *11*, 582. [CrossRef]
113. Koide, R.T.; Nguyen, B.T.; Howard Skinner, R.; Dell, C.J.; Adler, P.R.; Drohan, P.J.; Licht, M.; Matthews, M.B.; Nettles, R.; Ricks, K.; et al. Comparing Biochar Application Methods for Switchgrass Yield and C Sequestration on Contrasting Marginal Lands in Pennsylvania, USA. *Bioenergy Res.* **2018**, *11*, 784–802. [CrossRef]