

Applications and applicability of the cavitation technology

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Cavitation technology, encompassing acoustic and hydrodynamic methods, represents a transformative approach to process intensification, enabling high-efficiency energy and mass transfer across diverse industrial applications. Acoustic cavitation exploits high-frequency ultrasonic waves to generate transient and stable bubbles, leading to localized high temperatures, pressures, and reactive species formation. Hydrodynamic cavitation, achieved through fluidic devices, such as Venturi tubes and vortex diodes, generates cavities under controlled low-pressure zones, providing scalable solutions for large-scale operations. This study critically examines the industrial viability of cavitation technologies, emphasizing their unique ability to combine mechanical, thermal, and chemical energy release. A detailed comparative analysis reveals the limitations of acoustic cavitation, including energy attenuation and equipment wear, against the superior scalability of hydrodynamic systems. Key challenges, such as enhancing hydroxyl radical yield, reducing operational costs, and improving system robustness, are explored alongside potential synergies with complementary technologies, like advanced oxidation processes and photocatalysis. Emerging industrial implementations, including biogas enhancement and chemical processing, underscore the evolving landscape of cavitation-based innovations. This work highlights the necessity for multidisciplinary strategies, integrating experimental, computational, and engineering perspectives to advance cavitation technology. By addressing scalability and cost-effectiveness, cavitation systems can unlock transformative opportunities for sustainable industrial applications, aligning with global environmental and economic imperatives.

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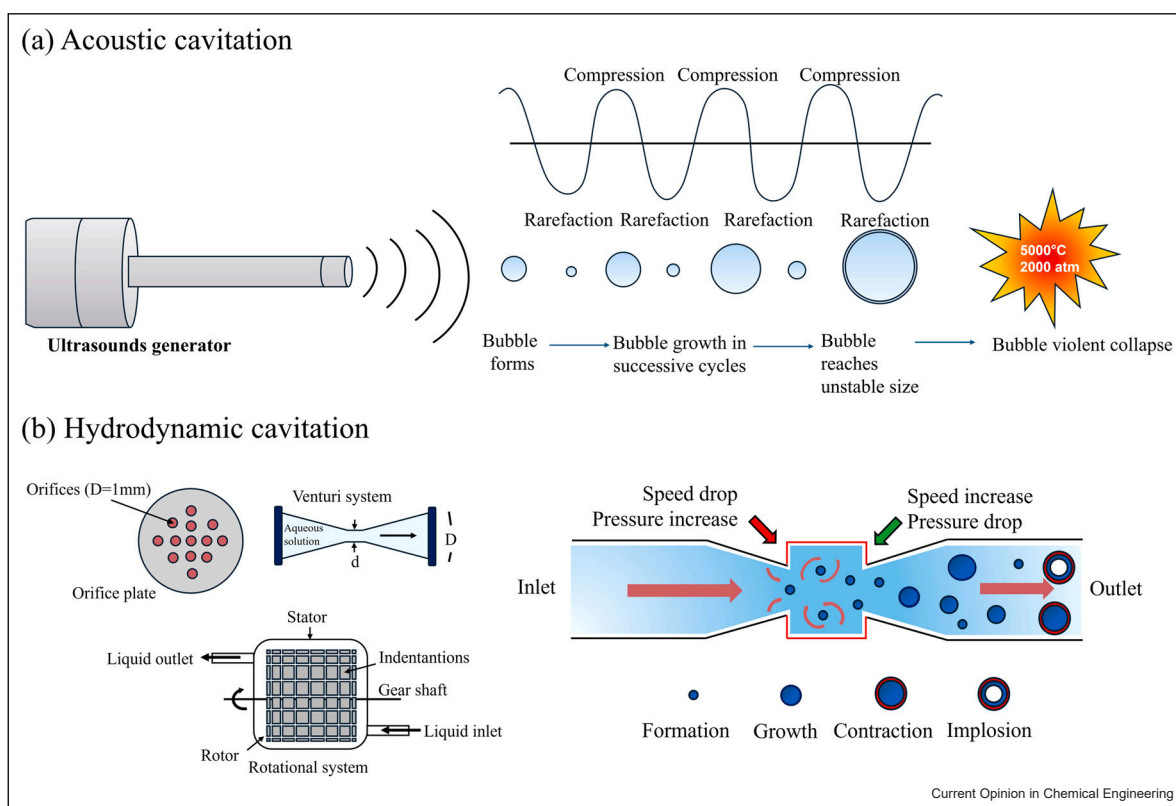
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Introduction

Cavitation is a physical phenomenon that occurs when the pressure in a liquid drops below its vapor pressure, leading to the formation and growth of gaseous pockets [1]. Once formed, these bubbles can implode or collapse when the local pressure increases, releasing a significant amount of energy in the process. This released energy can be used to break complex molecules and/or enhance the reactivity of certain reactions [1].

In the industrial sector, the two main types of cavitation relevant to industrial applications are acoustic and hydrodynamic. Acoustic cavitation, generated by ultrasound (20 kHz to 200 MHz), occurs when high-frequency sound waves lower the local pressure below the vapor pressure of the liquid (Figure 1a) [2]. By contrast, hydrodynamic cavitation is induced through fluidic devices that create localized low-pressure zones, where cavities form and collapse as they move with the flow to higher-pressure areas, releasing stored energy (Figure 1b) [3].

Figure 1



Schematic representation of the (a) acoustic and (b) hydrodynamic cavitation with examples of cavitators.

Cavitation's potential for industrial use lies in its unique characteristics: cavity collapse generates high-velocity jets, localized high pressures and temperatures, and hydroxyl radicals [1–4]. Additionally, cavitation produces heat, and bubble dynamics may cause local electrification and discharge [5–7], combining mechanical, thermal, and electrical energy release with reactive species generation. Acoustic cavitation devices, often employing piezoelectric or magnetostrictive transducers, achieve high power densities, with horn-type piezoelectric transducers producing several hundred W/cm^2 [8].

Hydrodynamic cavitation devices fall into two categories: active and passive (Figure 1). Active devices use moving parts, such as an impeller and stator, with their geometry, speed, and flow rate dictating cavitation extent [1]. Passive devices, which lack moving parts, create low-pressure zones through small constrictions (e.g. orifices, Venturi ducts) or swirling flows. Swirling-flow devices, like Ranade's vortex diode [1], mitigate clogging and erosion issues common in constriction-based systems, as bubble collapse occurs in the vortex core, away from device surfaces [9]. Both types of devices can be highly effective when combined with existing cavitation technologies, such as dual activity cavitation

reactors and solvent-assisted cavitation processes [10,11]. This integration enables more efficient and scalable real-world applications, aligning with current trends to make industrial processes more sustainable, cost-effective, and versatile.

With the aim of enhancing the efficacy of cavitation in these applications, the rigorous assessment of the aspects related to the number and quality of cavities, the intensity of cavity collapse, and the various mechanisms of intensification that promote hydroxyl radical formation, interfacial contacting, and other reactive effects is a crucial point. These factors play a fundamental role in optimizing cavitation for specific industrial applications, but a detailed analysis of literature data and advanced analytical techniques is needed [12]. Moreover, while the cavitation number serves as a useful theoretical tool for understanding cavitation dynamics, its application in real-world scenarios remains limited due to variable fluid properties, turbulence, and operating conditions, often complicating the use of models [3].

With all these premises in mind, this paper aims to illustrate the current industrial applicability of cavitation technology, particularly at large scales.

To assess the applicability of cavitation technology and, if possible, promote its use, this work proposes: *i*) a focus on the distinctive characteristics of the technology, namely the aspects of cavitation technology that are either absent or present to a lesser extent in competing technologies; *ii*) the identification of an appropriate figure of merit, allowing a comparison between cavitation technology and other competing technologies to determine if cavitation can be applied more effectively or efficiently in a specific application; and *iii*) the evaluation of the potential applicability of cavitation in combination with other technologies (in particular, cavitation may prove advantageous if effectively combined with complementary technologies, enabling synergetic interactions).

Ultrasound technology vs. acoustic cavitation technology

To identify the unique processes that can only be realized through cavitation technology, it is important to emphasize that transient acoustic cavitation technology is not synonymous with ultrasound technology. In other words, the effects produced by the propagation of ultrasonic waves through a (typically inhomogeneous) fluid should not be conflated with the effects of (transient) cavitation induced by those same waves. Ultrasound power is transferred to a fluid medium via several distinct physical mechanisms, including:

- i) *Electromechanical energy conversion*: Mechanical energy is directly transferred from the electroacoustic transducer (e.g. piezoelectric or magnetostrictive transducer) to the fluid. This mechanism is used, for example, to atomize liquids, that is, to break a bulk fluid phase into fine droplets of liquid [13].
- ii) *Mechanical vibration propagation*: Energy is transferred through successive particle collisions as the sound waves propagate through the medium [14]. This mechanism is typically employed to shift the particle size distribution towards smaller sizes, as seen in food homogenization processes [14].
- iii) *Rayleigh scattering*: Energy is scattered in various directions when ultrasound waves encounter small particles or air bubbles much smaller than the sound wavelength. This scattering process enhances the energy distribution uniformity within the medium [15]. It is commonly used for emulsification in cosmetics or pharmaceuticals fields [15].
- iv) *Absorption, viscous damping, and acoustic streaming*: Energy is absorbed by vibrating particles and dissipated into the medium through friction, generating heat [16]. This mechanism is applied in heat transfer intensification, accelerating physical and chemical processes across various industries [17].

Each of these mechanisms contributes to different industrial processes, but none of them replicate the specific

effects generated by transient cavitation. Cavitation-induced phenomena, such as high-velocity jets, localized pressures, and the formation of highly reactive chemical species, are not directly achieved through the propagation of ultrasonic waves alone. Thus, while ultrasound can transfer energy in multiple ways, only cavitation technology can uniquely harness these effects for industrial applications.

Gas vs. vapor bubbles

Acoustic and hydrodynamic cavitation generate bubbles with distinct characteristics. Stable acoustic cavitation at high frequencies produces bubbles that oscillate for hundreds of cycles [18], resulting in high bubble concentrations within the liquid. This property makes acoustic cavitation suitable for separation processes, such as flotation [19], which exploits the adhesion of small air bubbles to solid particles, causing them to rise to the surface [20]. Flotation is widely applied across industries, including paper, food, oil, and water treatment, leveraging high concentrations of small bubbles generated by pressurizing water to 4–6 atm, saturating it with air, and rapidly depressurizing to form bubbles [20].

Despite its potential, cavitation technology is generally less efficient than traditional air flotation for industrial separations, as bubble formation and collapse occur continuously during stable cavitation. However, laboratory studies indicate that hydrodynamic cavitation-induced particle disintegration can enhance processes, like coal flotation [21]. To improve separation efficiency, innovations, such as generating nano- instead of micro-bubbles, coupled with techniques to enhance bubble stability and density, may unlock cavitation's potential in advanced separation processes.

Innovation as the application of a technology

The application of technology must align with the principles of innovation, ensuring that it achieves productivity levels that meet market demands, complies with standards and regulations, and enables the creation of distinctive products. These products should address critical social or environmental challenges, such as reducing water pollution, while also generating economic value by fulfilling customer needs and expanding their potential for broader application.

Cavitation technologies are defined by their development level, which includes both immaterial and material components. The immaterial aspect encompasses knowledge, technical expertise, and intellectual property driving innovation. The material aspect involves the tools and equipment necessary for cavitation processes, technologies for analyzing the cavitating fluid and its medium, and advanced materials essential for fabricating key system components. Together, these elements

highlight the readiness and potential of cavitation technologies to deliver significant industrial and environmental impact.

The development level of cavitation technology is constrained by its intrinsic limitations. For example, a fundamental limit of acoustic cavitation is the unavoidable attenuation of sound intensity in a fluid. This intensity, denoted as E , decreases exponentially with distance x from the transducer surface, according to the equation ($E = E_0 \cdot e^{-\alpha x}$), where E_0 is the intensity at the transducer surface, and α is the attenuation coefficient [22].

Cavitation technology facilitates the production of valuable products with beneficial properties but also entails drawbacks that impact both capital and operational expenditures (CAPEX and OPEX). For instance, a key limitation of acoustic cavitation is the progressive erosion of transducer surfaces due to the mechanical effects of high-energy jets (measured in J/m^2) generated during the asymmetric collapse of cavitating bubbles [23]. These challenges must be carefully considered when evaluating the industrial scalability, cost-effectiveness, and long-term viability of cavitation technologies.

Regarding the industrial scalability of these technologies, recent developments focus on novel methods that improve the process, such as adding catalysts or using interactions at the surface of materials. Dual activity cavitation and solvent-assisted cavitation are two examples that offer many benefits. They make it easier to extract useful compounds and break down pollutants more efficiently. More in detail, on one hand, dual activity cavitation improves treatment effectiveness, speeding up the process. However, it can be expensive, since it uses more chemicals and energy [10]. On the other hand, solvent-assisted cavitation is more cost-effective and easier to scale up but raises concerns about the safety and environmental impact of using solvents [11]. Overall, both methods require the optimization of the operative conditions that can make them more complex to manage and maintain, and their widespread use requires careful attention to costs, energy use, and environmental effects.

Relative assessment of a technology through a figure of merit

Unless a given technology *enables* a selected application (i.e. the selected application is feasible *only* using the given technology), it is possible to perform its assessment *in a relative way*, that is, to evaluate if the given technology T^* 'is better than' a competing technology $T\sim$ for the selected application. We have now to replace ' T^* is better than $T\sim$ ' by specifying a *figure of merit*, which may enable a *quantitative* comparison between T^* and $T\sim$. In the case of cavitation technology (transient or stable acoustic cavitation, passive or active hydrodynamic cavitation),

according to the above-given definition of cavitation technology as a *fluid processing* technology, we may generally state the figure of merit as $Z = \text{impact of process}/\text{cost of process}$, where *process* should be normalized over a unit flow ($\frac{\text{m}^3}{\text{s}}$) of treated fluid (rather than over a unit volume (m^3), so that the *effectiveness* of the process is also taken into account). We define effectiveness as the time required to transform a unit volume (m^3) of fluid from a given initial state (e.g. featuring an initial particle size distribution of a suspended phase) to a final state (featuring a final particle size distribution).

A figure of merit of this type is the *electric energy per order* ($EEO = \frac{\text{kWh} \cdot \text{m}^3}{\text{order}}$) — the amount of electric energy required to bring a decrease in viable colony counts by one order of magnitude — which is often used for the assessment of advanced oxidation processes (AOPs) [24].

This general definition highlights both positive (e.g. pollutant molecule fraction that reacted with OH-species) and negative (e.g. the acoustic power, which is directly and indirectly transferred to the fluid, causing an unwanted increase in its temperature) impacts. Process costs must account for both capital expenditures (CAPEX) and operating expenses (OPEX), which are often combined into a single metric, such as the cost of ownership (COO).

Accordingly, the figure of merit can be defined as:

$$Z = \text{impact of process (technical effect)} / \text{COO}$$

This formulation allows for a comprehensive evaluation of a technology's efficiency and economic viability, integrating technical performance with cost considerations.

In this frame, to properly evaluate cavitation technologies, it is also essential to consider both semi-empirical and near-empirical methods for further assessing performance [4]. Although theoretical comparisons using figures of merit (like the impact/cost ratio) are helpful, real-world testing with experimental data is necessary. In practice, factors, such as fluid properties, device design, and operating conditions can affect performance in ways that theoretical models might not capture.

While figures of merit provide a general comparison, the true effectiveness of a cavitation device needs to be tested in real conditions. Using a semi-empirical approach helps improve the technology for better performance and cost-effectiveness in specific applications. Whether working with acoustic or hydrodynamic cavitation, integrating real-world data is key to refining theoretical models and improving the practical use of the technology.

Complementary technologies

Taking into account that a technology may not be able to provide the expected impact if it is the *only* technology which is used to implement the given process (e.g. the destruction of recalcitrant organic pollutants at laboratory scale may be enhanced if acoustic or hydrodynamic cavitation is coupled to Fenton chemistry [25]), its applicability should be evaluated by comparing the figure of merit of $T^* \otimes T_1^* \otimes T_2^* \otimes \dots \otimes T_N^*$ to that of $T_{\sim} \otimes T_1_{\sim} \otimes T_2_{\sim} \otimes \dots \otimes T_M_{\sim}$, where T_i^* and T_j_{\sim} are complementary technologies that may be coupled (\otimes) to T^* and T_{\sim} , respectively, to provide the expected impact.

In the context of separation processes, a technology combining air flotation, capable of generating a high concentration of bubbles in a liquid, with transient acoustic or hydrodynamic cavitation, which reduces suspended particle size, could enable innovative separation methods. The industrial feasibility of such an approach would, however, hinge on achieving a compelling figure of merit.

Although the integration of cavitation with other technologies has not been systematically explored, particularly about defining and quantitatively evaluating an appropriate figure of merit, scientific literature provides numerous examples of such combinations. AOPs are a prominent case where cavitation is paired with photocatalysis or chemical agents, such as O_3 , H_2O_2 , CH_3COOH , and Fenton's reagent, to enhance water treatment efficiency [26–28].

Evaluating the industrial applicability of any technology requires not only a detailed understanding of the scientific state of the art but also an assessment of the maturity and market availability of related products. Commercial products often represent the latest iteration of continuous technological evolution, incorporating improved performance metrics (e.g. a higher figure of merit) while reflecting lessons learned from prior developmental challenges. This perspective not only sheds light on the primary industrial applications addressed by these products but also helps identify gaps and opportunities for further innovation.

Nowadays, there are many emerging technologies worth mentioning, although not all of them are on the market yet. With this in mind and focusing on the industrial applications, the following provides a brief and necessarily incomplete overview of the main industrial implementations of both hydrodynamic and acoustic cavitation technologies. To enable clear assessments, a proper evaluation of their cost should be made. However, cost estimation depends on several factors (e.g. size of the plant, project scale, technology used, and any required customizations), which can lead to

significant variations in expenses. Moreover, company websites do not provide estimates of potential costs.

ULTRAWAVES GmbH, originating as a spin-off of Hamburg Technical University, employs ultrasound and cavitation for biomass treatment and sewage sludge pretreatment in wastewater plants, aiming to enhance anaerobic digestion and biogas production (Figure 2a) [29,30].

Weber Entec GmbH focuses on ultrasound systems for biomass disintegration to facilitate biogas production and handle solid waste, as well as sewage sludge pretreatment to support anaerobic digestion (Figure 2b) [31,32].

Hielscher Ultrasonics GmbH manufactures sonication systems for applications like biodiesel production and sonochemistry, though most of its processes rely on ultrasound-enhanced mixing rather than cavitation-specific effects. Earlier attempts to leverage cavitation energy release are no longer prominent in their offerings (Figure 2c) [33].

VT A Austria GmbH supplies systems for sewage sludge disintegration, reportedly improving biogas yields by up to 30%. A full-scale plant was installed in Poland in 2015, but further large-scale applications are not highlighted (Figure 2d) [34].

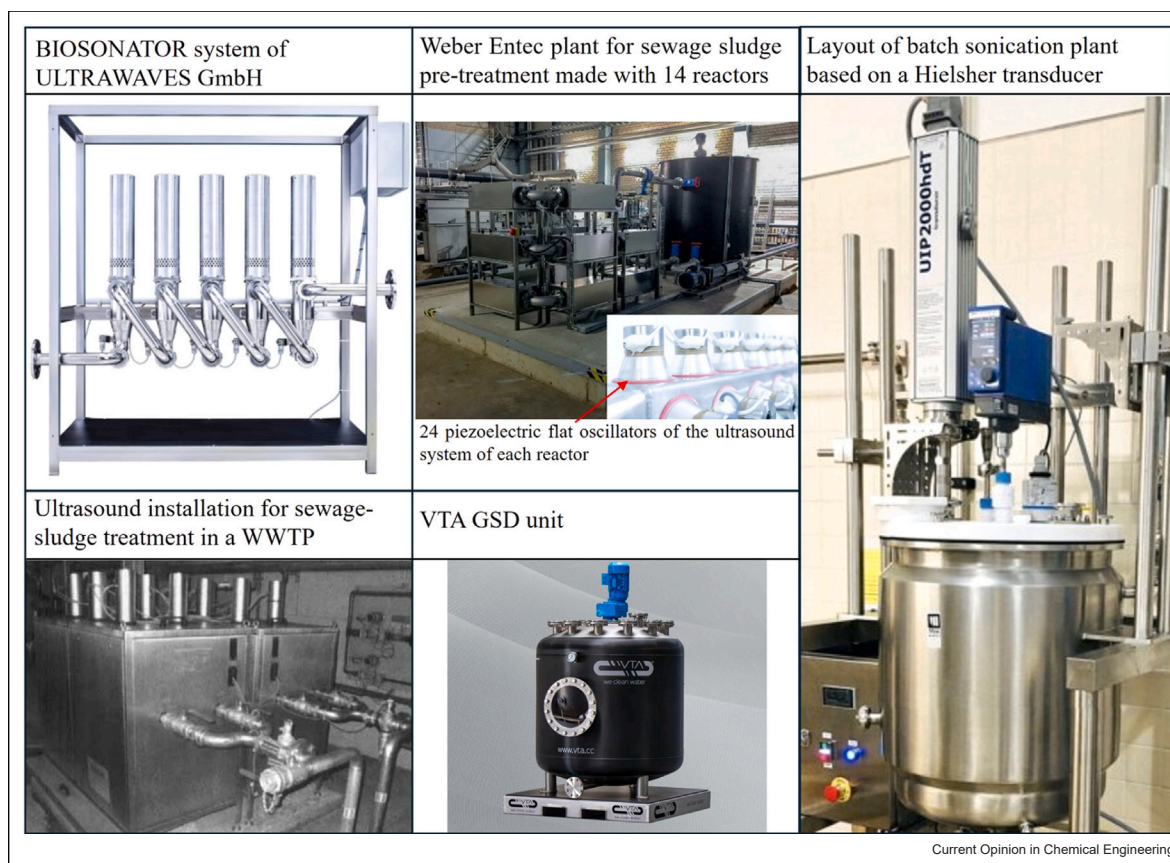
Cavitation Technologies, Inc. exploits static hydrodynamic cavitation technology by offering variable flow-through cavitation devices based on multijet nozzles (Figure 3a) [35,36]. Quoted at the NYSE (CVAT), the first pilot-scale tests of their technology happened in 2010. The company's balance sheets for Q3/2024 clearly show that cavitation business is yet to come.

Hydro Dynamics, Inc. provides pilot-scale active hydrodynamic cavitation reactors (Figure 3b), mainly addressing mixing, scale-free heating, process intensification, mass transfer, extraction, and biodiesel transesterification. No economic information for this company is available [37].

Mitton Cavitation Technology, Inc. provides active hydrodynamic cavitation systems based on previous innovations by Mitton Valve Technology Inc. (Figure 3c) [38,39]. It addresses the nutrient recovery from agricultural runoff, the remediation of water-based oil sands tailings and of food processing wastewater, the methane generation acceleration from bio-waste, the biofuel and ester harvesting, the starch recovery, and so on.

Three-es Srl, active in the field of high-pressure pumps, offers active hydrodynamic cavitation plants (Figure 3d) primarily designed for biomass treatment for biogas and biomethane generation [40].

Figure 2



Part 1: overview of some industrial implementations of acoustic cavitation technology [29,30,32–34].

Vorta is just one of the many companies exploiting vortex cavitation technologies (Figure 3e), mainly addressing pretreatment of Wastewater Treatment Plants streams to enhance biogas production [41]. However, Mane et al. have recently implemented vortex flow-based devices for destroying antimicrobial resistant bacteria, revealing superior performance compared to conventional orifice [42,43].

This brief overview of industrial acoustic and hydrodynamic cavitation systems highlights the current development level and primary applications of cavitation technology. Most companies focus on treating sewage sludge and lignocellulosic biomass, as noted by other authors [44]. Notably, despite its potential, sonochemistry, arguably the most distinctive application of cavitation, remains largely unexplored in industrial contexts.

Acoustic cavitation vs. hydrodynamic cavitation

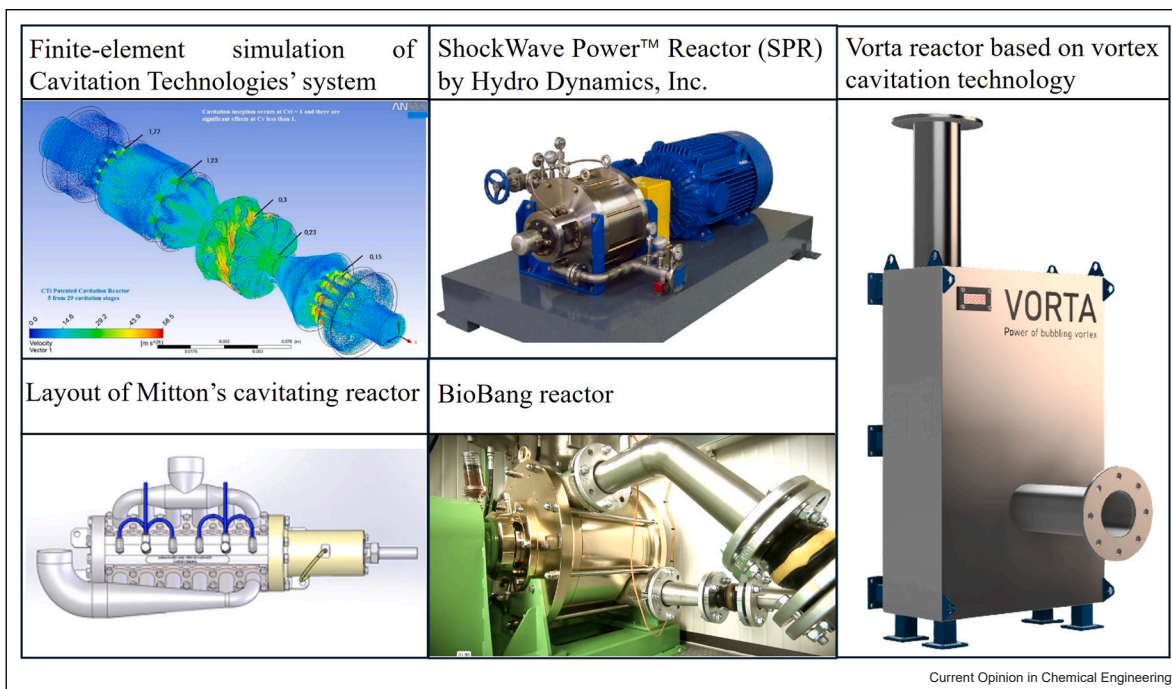
When looking for large-scale industrial applications, the scalability of a technology is a major issue. In particular

(see paragraph 5), the comparison of two different technologies, which compete for the same application by providing the same technical effect (e.g. by producing the same flow in $\frac{\text{mol}}{\text{m}^3\text{s}}$ of oxidants), such as acoustic cavitation and hydrodynamic cavitation, should consider the dependence of COO on the plant scale.

Generally speaking, both hydrodynamic and acoustic cavitation continue to evolve, even if the hydrodynamic approach appears to be more scalable than the acoustic one in various applications, including biodiesel production [45], treatment of effluents in Common Effluent Treatment Plants [46], oxidation processes combined with chemicals [47], microbial cell disruption [48], and processing of soy milk and egg white proteins [49,50].

Considering the higher COO of acoustic cavitation systems compared to hydrodynamic ones, further multidisciplinary research is needed to compare the technical effects of both technologies. This includes evaluating hydrodynamic cavitation's potential to surpass acoustic cavitation in key aspects, such as hydroxyl radical (OH·)

Figure 3



Part 2: overview of some industrial implementations of acoustic cavitation technology [35,37,38,40,41].

generation. Such assessments should rely on an appropriate figure of merit based on a technical effect in $\left(\frac{OH\cdot mol}{J}\right)$ [51].

According to these premises, integrating the distinct characteristics of acoustic and hydrodynamic cavitation into a combined technology could expand the scope of cavitation applications. This approach represents the recent direction in which research is moving, aiming to enhance performance and broaden the range of applications in industries, such as environmental remediation — particularly in wastewater treatment, where both forms of cavitation contribute to better pollutant breakdown and higher efficiency [47,52,53] — as well as in bioprocessing and medical treatments [54,55]. The ability to intensify processes and improve efficiency makes these combined solutions highly valuable technologies across a wide range of sectors. Advances in reactor design, understanding cavitation dynamics, and hybridizing these technologies are expected to drive further innovation and expand their industrial use in the coming years.

Main industrial applications and missing applications

Acoustic and hydrodynamic cavitation technologies are widely applied to treat municipal, industrial, and animal waste, as well as lignocellulosic biomass and agricultural

residues, enhancing anaerobic digestion and fermentation processes to significantly boost biogas production [56]. Beyond these large-scale uses, cavitation is employed in smaller-scale industrial applications, such as:

- *Food and Dairy*: Improving homogenization, emulsification, and extraction processes.
- *Cosmetics*: Enhancing product stability and texture.
- *Pulp and Paper*: Facilitating fiber treatment and reducing chemical use [57].
- *Oil and Gas*: Optimizing emulsification, degassing, and oil recovery [58–60].

Despite its potential, sonochemistry — the field most aligned with cavitation's unique capabilities — has yet to achieve widespread industrial adoption. By releasing localized mechanical, thermal, and electrical energy and generating reactive species, like hydroxyl radicals, sonochemistry can enable critical industrial reactions. However, its transition from laboratory to large-scale applications remains limited, leaving considerable untapped potential [61]. In this context, many authors have studied medium and large-scale configurations to optimize cavitation distribution in ultrasonic reactors. For example, Kumar and coworkers designed pilot reactors that are well-suited for further scaling up, following accurate measurements of local pressure and cavitation intensity [62]. Additionally, Professor Cravotto's research group developed a pilot system for reaction scale-up,

which was applied to the transesterification of soybean oil with methanol for biodiesel production [63] and a semi-industrial US-assisted extraction for grape-seed proteins [64].

Conclusions and future outlook

The industrial potential of acoustic and hydrodynamic cavitation hinges on their specific characteristics, development stage, inherent limitations, and alignment with industrial needs, all of which must be assessed using a quantitative figure of merit framework.

Despite extensive research into their chemical, physical, and engineering aspects, large-scale applications remain limited, with many implementations underutilizing cavitation's unique properties. Unlocking their industrial utility demands a multidisciplinary approach combining chemistry, physics, and engineering, supported by multiscale simulations to model cavitation's complex dynamics.

A tailored figure of merit should guide each application, reflecting technological requirements and implementation scale. Overcoming cavitation's limitations and fostering synergies with complementary technologies are crucial for developing transformative industrial solutions that exploit its distinctive energy dynamics and chemical reactivity.

Data Availability

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

Declaration of Competing Interest

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

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This review explores the mechanisms of cavitation and its impact on improving microbial activity and biogas yields. The authors discuss various cavitation techniques, their advantages, and challenges in scaling for real-world applications, highlighting potential environmental benefits and the future prospects of cavitation in optimizing biogas production systems.

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This paper explores the use of ultrasound technology for the extraction of grape-seed proteins, a valuable by-product of the wine-making process, in line with the principles of the circular bioeconomy. The authors compare the protein content of extracts obtained under silent and lab-scale conditions with those produced under semi-industrial ultrasound conditions. The study also examines the chemical composition, including carbohydrates, total phenols, and lipids, as well as the elemental profiles of the final, up-scaled extracts. These findings highlight the potential of ultrasound technology for efficiently extracting functional proteins from grape seeds, with applications in both nutrition and industry.