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Review

Controlled Hydrodynamic Cavitation: A Review of Recent Advances and Perspectives for Greener Processing

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Received: 30 December 2019; Accepted: 10 February 2020; Published: 13 February 2020

Abstract: The 20th century has witnessed a remarkable enhancement in the demand for varieties of consumer products, ranging from food, pharmaceutical, cosmetics, to other industries. To enhance the quality of the product and to reduce the production cost, industries are gradually inclined towards greener processing technologies. Cavitation-based technologies are gaining interest among processing technologies due to their cost effectiveness in operation, minimization of toxic solvent usage, and ability to obtain superior processed products compared to conventional methods. Also, following the recent advancements, cavitation technology with large-scale processing applicability is only denoted to the hydrodynamic cavitation (HC)-based method. This review includes a general overview of hydrodynamic cavitation-based processing technologies and a detailed discussion regarding the process effectiveness. HC has demonstrated its usefulness in food processing, extraction of valuable products, biofuel synthesis, emulsification, and waste remediation, including broad-spectrum contaminants such as pharmaceuticals, bacteria, dyes, and organic pollutants of concern. Following the requirement of a specific process, HC has been implemented either alone or in combination with other process-intensifying steps, for example, catalyst, surfactant, ultraviolet (UV), hydrogen peroxide (H_2O_2), and ozone (O_3), for better performance. The reactor set-up of HC includes orifice, slit venturi, rotor-stator, and sonolator type constrictions that initiate and control the formation of bubbles. Moreover, the future directions have also been pointed out with careful consideration of specific drawbacks.

Keywords: hydrodynamic cavitation; green processing; food processing; extraction; biofuel; emulsification; remediation

1. Introduction

The growing human population has impacted almost all industrial sectors to transform their existing technologies for better alternatives. Research interest on greener processing technologies has been on a steady rise, with significant contributions to technologies such as microwave (MW), pulsed electric field (PEF), ultrasound (US), hydrodynamic cavitation (HC), and plasma. Out of the range of technologies, HC has emerged as the best processing technology, while considering its scalability and efficiency. HC is a novel technique that has extensive applications, ranging from food processing to waste remediation. HC can be categorized based on the type of constrictions involved in the reactor design, which governs the cavitational phenomena. Considering food processing and extraction, HC can be superior compared to conventional methods in terms of solvent and energy consumption, improved product quality, and large-scale application. The HC-mediated extraction of lipids from microalgae, protein, and fatty acids from natural products has also demonstrated its advantages over conventional methods. The sustainable production of environmentally-friendly green fuel alternatives such as biodiesel, methanol, and ethanol could benefit energy sectors, while decreasing fossil fuel dependency and minimizing harmful greenhouse gases, as well as pollutant emissions [1]. In that context, HC provides superior biodiesel, biogas, bioethanol, and hydrogen yield from different types of wastes, as well as fresh natural matrix. The food processing, and specifically the brewing industry have seen the radical inclusion of hydrodynamic cavitation for process intensification, gluten reduction, and to retain certain healthy bioactive compounds. Besides this, with HC processing, the antioxidant activities and stability of bioactive compounds have been enhanced in food matrices [2]. Moreover, HC has been demonstrated to be remarkably effective in wastewater treatment, with high mineralization extent of pollutants and disinfection outcomes. Other than conventional wastewater treatment methods, which can only selectively remove a specific category of pollutants, the performance of HC spans a wide variety of contaminants, which has the potential to replace multistep treatment methods. Several investigations on HC-assisted treatment of pesticides, dyes, pharmaceuticals, and cyanobacteria have indicated its ability in the elimination of the concerned contaminants [3,4].

In general, HC finds its application in a broad category of greener processing methods, while demonstrating efficient utilization of energy and resource. We have extensively reviewed the application of HC for a range of processing requirements, and this review contains detailed information, as well as a discussion on HC-assisted extraction, emulsification, food processing, biofuel synthesis, and wastewater remediation.

2. Principles of Hydrodynamic Cavitation

The principle of hydrodynamic cavitation (HC) is based on the passage of the liquid through a constriction (orifice plate, venturi, throttling valve), resulting in an increase in liquid velocity at the expense of local pressure, as well as a fall in pressure around the point of vena contracta below the threshold pressure, which supports the formation of cavities. The subsequent implosion of cavities takes place due to the expansion of liquid jets at the downstream of constriction as the pressure recovers [5]. The schematic diagram of non-rotating hydrodynamic cavitation reactors is represented in Figure 1, where it demonstrates the setup with types of constrictions. The hydrodynamic cavitation (HC) system consists of a feed tank, a plunger pump for circulating the solution through the reactor, a pressure gauge, and the cavitation chamber, which consists of constrictions either in the form of an orifice, venturi tube, or throttling valve for bubble generation. Other than the type of constriction, HC can also be categorized based upon its operating ways, as: (a) a pulsating hydrodynamic cavitation reactor—operating the reactor in pulsations (cycles); (b) continuous hydrodynamic cavitation reactor; (c) shear-induced hydrodynamic cavitation reactor.

The generated cavities go through transient collapse events while generating a temperature of up to 10,000 K, as well as high-pressure shock waves and free radicals [6], which could induce physical and chemical changes to the target matrix. The cavitation number is an essential factor of HC, which could be estimated based on the following Equation (1):

$$\text{Cavitation number } (\mathrm{C_v}) = \frac{(P_2 - P_v)}{\frac{1}{2}\rho V^2}, \tag{1}$$

where P_2 is the fully recovered downstream pressure, P_v is the saturated vapor pressure of the liquid, ρ is the density of the liquid, and V is the average velocity of the liquid at the constriction. The initiation of cavitation starts at a threshold cavitation number known as the cavitation inception number. With an increase in inlet pressure, the volumetric flow rate through the orifice increases, and the velocity at the constriction of the orifice also increases, resulting in a decline in cavitation number. Generally, cavitation occurs at $\mathrm{C_v} \leq 1$, but cavities can also be formed at a value greater than 1 owing to the presence of dissolved gases and other solid particles in the liquid [7]. The HC setup and hydrodynamic cavitating devices, as shown in Figure 1, are non-rotating devices, and the intensity of a cavity collapse or the cavitational yield depends on the geometry of the cavitating device. The number of cavities that are being generated, residence time of cavities in the low-pressure region, and the cavity collapse pressure can be affected by the change in the geometrical parameters, such as throat area, throat perimeter, size and shape of the throat, geometrical configuration (venturi or orifice), and convergent and divergent angle of the venturi [8]. Many researchers have reported that the geometrical parameter "α", which is the ratio of throat perimeter to the throat cross-sectional area, should be kept high for higher cavitational yield. The α can be increased either by changing the shape of the throat, i.e., rectangular or elliptical shapes can be used instead of circular, or by increasing the number of holes of smaller sizes [9]. It has also been reported that the venturi-based HC devices produce better cavitational yield than the orifice plates, since venturies produce more cavities and allow cavities to grow to maximum size before they collapse, due to the smooth recovery of pressure in the downstream. Venturies produce stable cavitation and are mainly used for carrying out chemical transformations, such as wastewater treatment. On the other hand, orifice-based HC devices produce transient cavities due to the sudden pressure recovery in the downstream, and therefore are mainly used for applications where high shear is required, such as emulsification, particle size reduction, and mass transfer-driven chemical reactions [8,9].

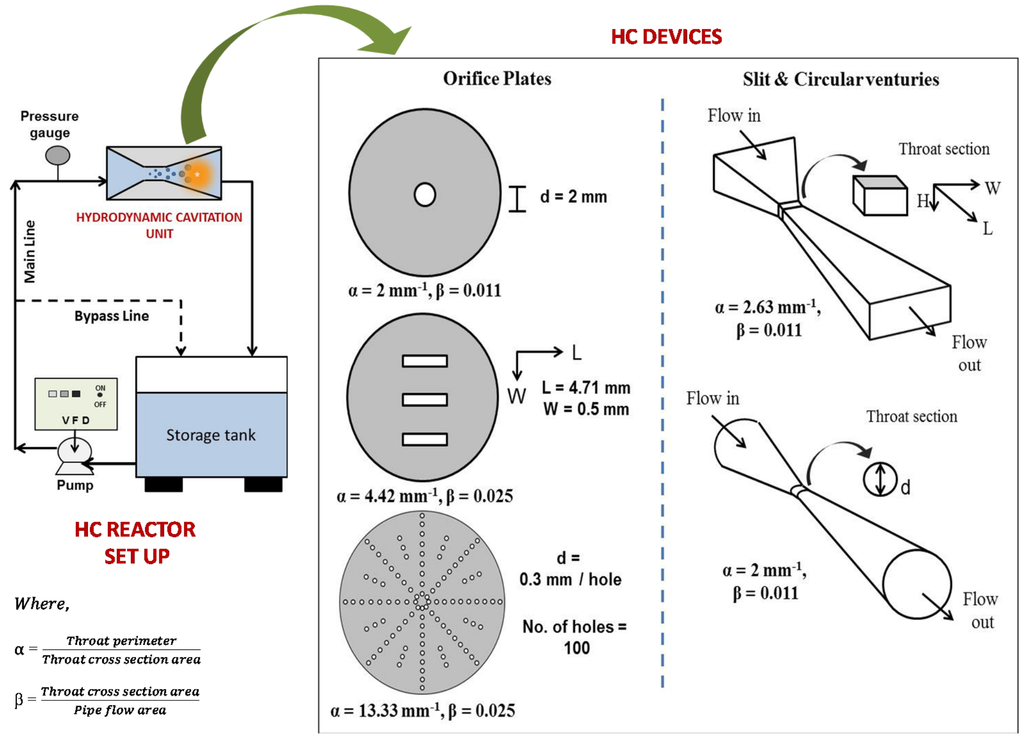

Figure 1. Schematic of the hydrodynamic cavitation (HC) reactor setup and hydrodynamic cavitating devices based on venturi and orifice plate (non-rotating) (reproduced with permission from Carpenter et al. 2017 [8] and Bargole et al. 2019 [9]).

3. Emulsification

The emulsification process of dispersing a liquid into another immiscible liquid is an important step in cosmetic, food, pharmaceutical, or nutraceutical industries. The emulsification process is supported via the bubble collapse near the liquid–liquid boundary, thereby lowering the interfacial tension and breaking the interface to facilitate the dispersion of droplets in the continuous phase. Moreover, the mechanism of emulsion formation could take place via the cavity collapse in a less viscous oil phase, which generates high micro-turbulence and is responsible for the increase in the interfacial area between two immiscible phases. Regarding the type of emulsions, nanoemulsions, as compared to macroemulsions, have specific significance in food, pharmaceuticals, cosmetics, and paints that require an appropriate amount of energy to achieve the desired droplet size. Conventional high-energy approaches, such as mechanical agitation (homogenizer, fluidizer, colloid mills) and acoustic cavitation (ultrasound processor) methods, are reported to be inefficient for large-scale processing due to their poor energy efficiency [8]. Moreover, low-energy approaches, for example, membrane emulsification and microchannel emulsification, suffer from drawbacks of low dispersed phase flux, poor control over achieving the desired droplet size, and higher fabrication and operating cost. In that aspect, HC has been proposed as a better option for producing nanoemulsion of desired droplet size even under a large-scale setup.

Low-pressure hydrodynamic cavitation (LPHC) was utilized for the preparation of mustard oil in a water nanoemulsion with the smallest droplet size of 87 nm, in the presence of emulsifiers such as Span 80 and Tween 80 [8]. The comparison among constrictions for obtaining the emulsion of the smallest droplet size indicated slit venturi to be ideal, followed by circular venturi and orifice plate. The prepared nanoemulsions exhibited excellent physical stability of up to three months, demonstrating the effectiveness of HC over other conventional techniques. It was also observed that the maximum size reduction was obtained at an inlet pressure of 10 bar, for which the cavitation numbers were found to be in the range of 0.17–0.20 for all the devices, and beyond this pressure, further droplet size reduction was not witnessed. Similar observations were also noted by Ramisetty et al. [10], wherein they reported the preparation of coconut oil in water emulsion using two different types of hydrodynamic cavitating devices—circular and slit venturi (Table 1). The emulsion was stabilized using a mixture of tween 80 and span 80 emulsifiers. The minimum droplet size of 200 nm was achieved using circular venturi in 30 min at an inlet pressure of 10 bar, internal phase volume fraction (coconut oil to water) of 0.1, and surfactant volume fraction of 0.055. However, the rate of droplet size reduction was found to be higher in the case of slit venturi. The droplet size reduced over two times for the case of slit venturi as compared to circular venturi, at 5 bar. Also, LPHC has been utilized to produce refined soybean oil-, heptane-, and castor oil-in-deionized water emulsions in the presence of sodium dodecyl sulfate as the emulsifier (1.25%), while generating average emulsion droplet sizes of 27 nm. With an increase in inlet pressure and surfactant concentration, the droplet size decreased [11], and the prepared emulsion was shown to be stable for up to eight months.

Table 1. Emulsion generation using hydrodynamic cavitating devices.

Emulsion	HC Reactor	Parameters	Smallest Droplet Size (nm)	Ref.
O/W: Mustard/Water	Venturi (slit)	Surfactants (8% *v*/*v*): Tween 80, Span 80; C_v: 0.19 (10 bar); CP: 200; Time (min): 90	87	[8]
O/W; Coconut oil in water	Venturi (circular and slit)	Surfactants (5.5% by volume): tween 80 and span 80; Inlet pressure (bar): 10; Time (min): 30	200	[10]
O/W: Soybean/Heptane/ Castor/Water	Orifice	Surfactants (1.25 wt%): SDS; Inlet pressure (psi): 120; CP: 6	27	[11]
Turmeric oil in skimmed milk	Venturi (circular)	Surfactant: SDS; Inlet pressure: 5 bar; Time (min): 45	246.5	[12]
Soy protein isolate	Swirling Jet	Pressure (MPa): 0.6; Time (min): 60	-	[13]

O/W: oil in water, CP: cavitation pass; SDS: sodium dodecyl sulfate.

Other than just oil in water (O/W) emulsions, HC has also been used to produce turmeric oil in skimmed milk emulsion under different types of reactor setups [12]. Among the three different HC setups, circular venturi was demonstrated to be the most efficient for obtaining stable emulsions. Yang et al. [13] demonstrated enhancing the emulsifying properties of soy protein via HC-assisted processing, which could hardly be achieved by other conventional methods. The soy protein isolate (SPI) was investigated under swirling jet cavitation, and the emulsions formed after HC processing indicated excellent emulsifying properties. The characteristics of SPI, such as emulsifying activity index (EAI), emulsifying stability index (ESI), percentage of adsorbed proteins (AP%), and creaming stability, have been significantly improved with the introduction of cavitation. Following the increase in cavitating pressure and treatment duration, properties such as EAI and ESI were improved, which could be attributed to the enhancement in matrix solubility with the duration of treatment. In the case of palm oil and multiple submicron emulsions preparations, a liquid whistle hydrodynamic cavitation reactor (LWHCR) was used by Parthasarathy et al. [14] and Tang et al. [15]. A droplet size of 476 nm was obtained at an operating pressure of 5.5 MPa, whereas multiple emulsions of less than 600 nm droplet size were achieved.

4. Extraction

The extraction of essential molecules from natural products and their respective applications in food, pharmaceutical, and cosmetic industries has been growing in recent years. Proteins, natural dyes, essential oils, and flavors can be effectively extracted by cavitation-based techniques, such as ultrasound and HC. Even though ultrasound-based extraction finds wider applications [16], HC has drawn growing interest due to its potential for scale-up application and efficiency. Oleaginous microorganisms are a vital source of lipids (neutral lipids, phospholipids, glycolipids, free fatty acids) that could be extracted by HC via different reactor set-ups. A venturi type HC was utilized by Lee et al. [17] for the extraction of lipids from wet microalgae (*Nannochloropsis salina*), which demonstrated a higher lipid extraction of up to 99% as compared to 26.9% yield via the ultrasound-assisted method. To enhance the lipid extraction from wet microalgae, the orifice-type HC has also been considered [18], and computational fluid dynamics (CFD) have been utilized to optimize the essential parameters of flux, flow rate, and the number of passages. The outcomes pointed to the highest extraction yield under minimized surge pressure and with an increase in vapor fraction as well as the number of fluid passages. However, it was noted that the extent of cell disruption is not linearly related to the cavitation number. Considering dry *Nannochloropsis* sp. microalgae, HC has also demonstrated high lipid extraction efficiency, which could play a vital role in biodiesel production [19]. HC can also be utilized to extract proteins from plants, which was reported by Preece et al. [20] for the extraction of soy protein with better yield compared to ultrasound-based extraction (82% versus 70%). The enhanced yield could be attributed to the higher number of bubble implosions and the resultant structural disruption of soy flakes. Grillo et al. [21] utilized a pilot-scale (25 L) rotor-stator HC reactor for the extraction of valuable compounds (flavonols, methylxanthines, fatty acids, polyphenols, cocoa butter) from cocoa bean shell, that was accurately evaluated by gas chromatography-mass spectrometry (GC-MS)- and liquid chromatography-mass spectrometry (LC-MS)-based analysis. While methylxanthines are determined by the diode array detector (DAD) of high-performance liquid chromatography (HPLC), fatty acids and polyphenols were detected by GC and LC-MS analysis, respectively. The selective extraction of enzymes from yeast was successfully performed by Mevada et al. [22], with the adaptation of combined pretreatment strategies of hypoosmotic acidic stress and the addition of reducing agents for better efficiency. With the complementary effect of HC, acidic stress, and the reducing agent (Dithiothreitol), the cell wall disruption was shown to be enhanced, resulting in 4.79-times higher selectivity in the recovery of the periplasmic enzyme. Besides this, HC demonstrated 63.19-times greater energy efficiency as compared to high-pressure homogenizer. Considering green extraction or solvent-free extraction capabilities, HC has also demonstrated remarkable extraction yield in the case of bioactive compounds from Silver Fir (Abies alba Mill.) needles [23] and waste orange peel [24].

With only an aqueous solution as the extraction medium and a venturi-type HC reactor, the yield of total phenolic content (TPC) and total flavonoid content (TFC) from Silver Fir was noted to be 0.14 mgGAE/mL and 0.55 mgCE/mL, respectively. Considering waste orange peel, the extraction of pectin, polyphenols (flavanones and hydroxycinnamic acid derivatives), and terpenes (mainly d-limonene) has shown high yield within just 10 min of large volume (230 L) processing. Table 2 lists the vital products extracted by HC-based method.

Table 2. Vital products extracted by HC-assisted method.

Matrix: Extract	Reactor	Parameters	Yield	Ref.
Microalgae Nannochloropsis salina (wet): Lipids	Venturi	Cv: 1.17; ED (min): 25.05	99%	[17]
Microalgae Nannochloropsis salina (wet): Lipids	Orifice	Inlet pressure (bar): 4; T (°C): 60; ED (min): 20	46.0 ± 3.7%	[18]
Microalgae Nannochloropsis sp. (dry): Lipids	Venturi	Cv: 0.126; T (°C): 42; ED (h): 2	93%	[19]
Soybean: Protein	Venturi	Inlet pressure (MPa): 100	82%	[20]
Cocoa bean shell: Theobromine Caffeine Fatty acids	Rotor/stator	RPM: 3000; ED (min): 11	160.2 mg/g 8.9 mg/g 964 mg/g	[21]
Yeast: Enzyme	Orifice	Pressure: 6 bar; T (°C): 50	55.78 U/mL	[22]
Silver Fir: Phenolics Flavonoids	Venturi	RPM: 2900; ED (min): 60; T (°C): 67.5	100%	[23]
Waste orange peel: Pectin Polyphenols Terpenes	Venturi	RPM: 2900; ED (min): 10; T (°C): 20	60% 45%	[24]

Cv: Cavitation number; ED: Extraction duration; T: Temperature.

5. Food Processing

With growing consumer demand, numerous food products require a range of processing steps to be able to meet food standards, tastes, etc. Besides this, broader interest in implementing greener processing technologies has been on the rise, considering both processing costs and to eliminate the usage of harmful chemicals. In this context, HC has found its application in food processing in recent years, which could be envisaged to grow further.

Beer is the most favorable alcoholic beverage across the world, with the consumption of around 200 billion liters per year [25]. Considering the emerging brewing technologies, HC can be involved in the process, and could improve production stages in terms of energy efficiency, productivity, and quality. Controlled HC has been successfully implemented in beer brewing while demonstrating overall benefits, such as escalating enzymatic saccharification, enhancement in starch extraction, and reduction in processing time by replacing traditional demanding steps, such as dry milling and boiling. Moreover, the reactor could be easily maintained due to the simple structure of HC as compared to the multistep conventional brewing arrangements. In addition to the process benefit of brewing, HC has also served as the one-step solution to water and wort disinfection. Even though beer contains many healthy ingredients, the presence of gluten is unsuitable for coeliac disease patients [26]. The effort to produce gluten-free (<20 mg/L) and low gluten content (<100 mg/L) beer is gaining interest among producers, with the potential of a billion-Euros market, even only in Europe [27]. Important to note that for industrial-scale brewing, the venturi-type reactor was identified as the most appropriate HC setup, rather than orifice or rotor-stator [28]. Albanese et al. [29] provided evidence of reducing the concentration of gluten during controlled HC-assisted brewing of barley malts without using any additives. Similarly, Ciriminna et al. [30] also used controlled hydrodynamic cavitation as a replacement for critical steps in beer-making, such as mixing water with grains, whole mashing, and hopping. Moreover, they could retain and generate essential and unique bioactive compounds, such as prenylflavonoids xanthohumol (XN), desmethylxanthohumol (DMX), and 6-geranylnaringenin (6-GN) from hops (Humulus lupulus), during the process of brewing, which are known for their antithrombotic, hepatoprotective, anti-atherosclerotic, anti-carcinogenic, antioxidant, and antibacterial properties. Hops prenylflavonoids (XN, DMX, 6-GN) were measured via ultra-high-performance liquid chromatography, heated electrospray, and mass spectrometry (UHPLC-HESI-MS) analyses. Other than the HC-based brewing technique, the essential bioactive compounds are deemed to be lost during the conventional brewing process due to incomplete extraction, adsorption to insoluble malt proteins, and yeast cells during fermentation. Table 3 lists the examples of HC applicability in food processing.

To enhance the solubility of milk protein-concentrate throughout storage, and to modify other functional properties of proteins, such as viscosity, gelling, and emulsification, either physiochemical, enzymatic, or chemical processing is usually employed. Li et al. [31] utilized an APV Cavitator (SFX technology, Denmark) as a medium of controlled hydrodynamic cavitation to study the changes in the functional properties of milk protein concentrate (MPC80). The outcomes suggested the application of HC-based pretreatment, which could effectively and efficiently alter the viscosity, solubility, wettability, and the particle size of milk protein. MPC80 viscosity was observed to decline up to 56% under HC processing. The quality of milk protein concentrate (MPC) powders is also dependent on its rehydration characteristics, and mostly the rehydration property of MPC deteriorates with the duration of storage. HC has also been implemented in a semi-industrial pilot scale level for the immediate rehydration of high protein milk concentrate [32]. The HC has outperformed conventional high shear mixing in terms of rehydration (90% milk powder; average particle size: 0.45 µm versus 21.17 µm), viscosity reduction, stability, and sedimentation. Guar gum (GG) finds its application in food processing, pharmaceuticals, personal care, and biomedicals, due to its low cost, biodegradability, and nontoxic properties [33]. The HC-assisted depolymerization of GG was investigated by Prajapat et al. [34], and under optimum conditions (inlet pressure: 4 bar, temperature: 32 °C), a decline of 70% in the intrinsic viscosity was observed, indicating the depolymerization of GG. However, with the addition of potassium persulfate (KPS) during the HC process, a 96% reduction in the viscosity was observed following 1 g/L loading of KPS. The extent of depolymerization was compared among three different HC reactor set-ups (orifice plate, slit venturi, circular venturi), and the slit venturi proved to be the most effective. Moreover, it was noticed that the chemical identity of GG did not change after HC treatment, which has also been confirmed by Fourier transform infrared spectroscopy (FTIR) analysis. The antioxidants present in fruits, plants, and vegetables can prevent cardiovascular diseases, cancer, premature aging, making them one of the most valuable ingredients. There is a high demand for antioxidants in cosmetic, pharmaceutical, and food industries due to their property of preventing the cell oxidation process. Other than the extraction of antioxidants, if the antioxidant activities in the food ingredients can also be improved during their processing, that can add essential benefits to the consumers. Lohani et al. [35] demonstrated the application of HC along with fermentation to obtain improved antioxidant activity in sorghum flour (SF) and apple pomace (AP). Under optimized conditions, the total phenolic content (TPC) of SF and AP was 39.5% and 42%, respectively, which was 11.2% and 7.2% higher than the untreated samples. The antioxidant activity (AA) of SF and AP increased by 9.9% and 4.4%, respectively. HC has found its application in tomato juice processing as well [36], and the technology is expected to be opted by other juice making industries in the future. The treated tomato juice exhibited higher stability of up to 14 days and better microbiological quality (less susceptible to microbiological degradation over time). Moreover, the contents of lycopene (carotenoid) and phenolic compounds were not altered during the treatment. Lycopene is known for its antioxidant activity, and HC has been shown to preserve and enhance its stability during the processing, whereas it could degrade under conventional thermal treatments.

Table 3. Applicability of HC in food processing.

Food type	Goal	Reactor	Outcome	Ref.
Beer	Overall brewing	Venturi	Speed up enzymatic Saccharification; 30% higher starch extraction; Reduction in processing time; 30% greater energy saving; Disinfection	[28]
	Gluten reduction	Venturi	Gluten content reduced significantly (>270 mg/L to <20 mg/L)	[29]
	Hops bioactive compounds retention/generation	Venturi	Retained XN, DMX, and 6-GN	[30]
Milk	Milk protein (MPC80) modification	Rotor-stator/sonolator	Reduction in viscosity; Increase in bulk, tapped density	[31]
	Milk protein concentrate powders (MPC80) rehydration	Rotor-stator/sonolator	Significant reduction in the particle size of milk powder	[32]
Guar gum	Depolymerization	Slit venturi	Viscosity reduced effectively	[33]
Sorghum flour; Apple pomace	Antioxidant activity enhancement	Rotor-stator/sonolator	11.2% and 7.2% enhancement of TPC in AP and SF	[35]
Tomato juice	Homogenization, Bioactive compound stabilization	Orifice	Lycopene and phenolic compounds stability enhanced	[36]

6. Biofuel

There is an unprecedented increase in the consumption of fossil fuel following ever-growing vehicle usage and industrialization. Increasing and affordable production of alternative biofuels could reduce the harmful environmental impacts of conventional petroleum-based products. Alternative biofuels, such as biodiesel, biogas, and bioethanol, hold specific significance because of their high heating values, which are well comparable to conventional fossil fuels. Moreover, the biodegradability, renewability, and non-toxic nature of biofuels make them superior candidates compared to fossil fuels. Therefore, the best effective bio-fuel synthesis routes need to be explored, following which the HC-based method has been shown to have superior capability in intensifying the associated process of esterification and others. The feedstocks for biofuel production could vary, however, non-edible oils such as neem, cotton, jatropha, and karanja, and waste vegetable, animal fat, and algae could be ideal for this purpose. Also, biofuel production can be obtained from edible oil, which serves as the feedstock of 95% of today's biodiesel production, which is neither cost-effective nor a better option while considering the potential risk of food crisis. Industrial-scale biodiesel production is mostly performed by the catalytic conversion of oil to fatty acid alkyl ester and glycerol in the presence of methanol. However, the process results in a low mass transfer rate, high energy requirement, and hence an increase in the production cost. Even though many alternative intensification technologies, such as microwave, ultrasound, and supercritical conditions, have been opted for biodiesel production, there is a limitation either in scale-up or cost-effectiveness. In that aspect, HC could be the best option for industrial-scale production of biofuel due to its energy efficiency, high product quality, and eco-friendly application.

Maddikeri et al. [37] utilized HC for intensification in biodiesel synthesis from waste cooking oil, which demonstrated a yield of up to 90%. The maximum yield was obtained under a slit venturi type reactor in comparison to the orifice plate and circular venturi type HC reactor. The role of turbulence induced by cavitation is largely responsible for the enhanced biodiesel yield. Chuah et al. [38] reported obtaining an eight-fold higher biodiesel yield than mechanical stirring via the application of HC, which intensified the alkali-catalyzed transesterification of waste cooking oil while reducing the reaction time by even six-fold compared to mechanical stirring (90 min to 15 min). The conversion rate was up to 98% within just 15 min of reaction, with superior yield (8.33-times higher) as well as energy efficiency (1.8-times higher) than the conventional mechanical stirring method. The biodiesel derived from waste cooking oil via HC is also a potential candidate for application in diesel engines, which could reduce the emission of hydrocarbon, carbon monoxide, and harmful particulate mass concentration [39]. Similarly, for the HC-based methyl ester conversion of non-edible rubber seed oil, Bokhari et al. [40] obtained 6.5- and 4.9-fold higher energy efficiency and reaction rate, respectively, as compared to mechanical stirring. They also reported utilizing a 21-hole orifice plate HC reactor for intensifying the production of biodiesel while obtaining 3.4- and 3.2-fold higher reaction rate and yield efficiency, respectively, than mechanical stirring. Understanding the need for pilot-scale production of biodiesel, HC has also been implemented by Bokhari et al. [41] to intensify the production from rubber seed (*Hevea brasiliensis*) oil. Considering edible oil, Ghayal et al. [42] demonstrated the synthesis of biodiesel from used frying oil with maximum efficiency under optimized HC orifice plate geometry of 2 mm hole diameter, consisting of 25 holes in total. Under optimized conditions, the methyl ester conversion was more than 95% of triglycerides during just 10 min of reaction time, which also indicates a highly effective cavitation yield (1.28×10^{-3} g/J) and the usefulness of HC as a superior intensification technology. Moreover, it has been observed that the flow geometry of the orifice plate is vital for the intensification of reaction. A new approach of using a rotor-stator type HC was implemented by Crudo et al. [43] to produce biodiesel from palm oil. For biodiesel synthesis, specific parameters, such as catalyst loading, operating temperature, reaction time, HC inlet pressure, and oil to alcohol ratio, hold significance for better yield [44]. Chitsaz et al. [45] utilized response surface methodology (RSM) to study the optimum conditions required for biodiesel production via the HC process. Moreover, biodiesel production was verified by GC-MS and FTIR analyses, indicating the maximum yield of up to 97.56% within just 8 min of reaction time. The GC-MS spectrum distinguished between the type of methyl esters of fatty acids, which indicated the presence of palmitoleic acid, linoleic acid, stearic acid, palmitic acid, and oleic acid in biodiesel, whereas the FTIR spectrum indicated the presence of impurities. Similarly, Bargole et al. [9] decided the optimum conditions of HC via RSM in biodiesel synthesis from waste cooking oil, which demonstrated a 100-hole orifice plate to be superior compared to venturi or single-hole orifice, resulting in 99% yield within just 5 min of treatment.

In addition to biodiesel, biogas and bioethanol are also the best alternative fuels to be investigated for scale-up. Lignocellulose biomass is one of the best available natural sources that has the potential for bioethanol production. However, the lignocellulosic biomass consists of cellulose, hemicellulose, lignin, and in particular, the crystalline structure of cellulose obstructs the enzymatic hydrolysis. Several pretreatment methods, including ammonia fiber explosion, acid or alkaline treatment, hydrothermal treatment, and microwave irradiation, were already explored to amend the lignocellulosic biomass contained in SCB to be susceptible to enzymatic hydrolysis. However, they are not efficient [46]. Kim et al. [47] adopted HC as a pretreatment tool for lignocellulose bioethanol production from reed. Under optimum conditions (3.0% NaOH, 11.8% biomass loading) of HC pretreatment and simultaneous saccharification, as well as fermentation (SSF), a yield of 25.9 g/L ethanol was obtained within 41.1 min.

Hilares et al. [48] employed interconnected HC reactors as the pretreatment method, followed by simultaneous saccharification and fermentation for ethanol production from sugarcane bagasse. The pretreatment enhanced the enzymatic hydrolysis, resulting in the enhancement of cellulose contents and the overall production of 17.26 g/L of ethanol. Similarly, Madison et al. [49] also implemented HC and US as the pretreatment strategies for sugarcane bagasse-based lignocellulosic biomass and reported an enhancement in the enzymatic digestion. Compared to only lime-treated bagasse, the HC followed by lime pretreatment demonstrated an enhancement of 46% in the enzymatic digestibility, which indicates the significant role of hydrodynamic cavitation on the structure of cellulose. HC-based pretreatment also enhanced the ethanol yield from dry mill corn in a pilot-scale setup, while demonstrating a 2.6% higher yield under optimum conditions [50].

Like bioethanol, biogas (methane) has enormous potential to replace conventional fossil fuels, and added to that, it could be effectively synthesized from lignocellulosic biomass. To enhance the microbial degradation of biomass, HC could be a suitable pretreatment choice that could reduce the structural hindrance present in lignocellulose biomass for productive digestion. Both Patil et al. [51] and Garuti et al. [52] opted for HC as the pretreatment step to enhance biogas yield from wheat straw and agricultural biomass (pig slurry, maize silage, triticale silage, beet molasses, cornmeal), respectively. The biogas yield efficiency (172.3 mL/g) indicated the combined HC-based treatment to be better than KOH-mediated alkaline pretreatment. Habashi et al. [53] reported the application of HC as a novel pretreatment step to enhance biogas production during the co-digestion of oily wastewater and waste-activated sludge, while achieving a 30% enhancement in the total biogas production. Saxena et al. [54] reported the efficacy of the pretreatment method of tannery waste effluent (TWE) by HC before anaerobic digestion (AD) using a slit venturi. The biogas yield and chemical oxygen demand (COD) reduction were increased two-fold when HC was used as a pretreatment unit to the AD. The HC pretreatment of TWE caused an increase in the acetogenesis and methanogenesis reactions during the AD process, which ultimately resulted in the enhanced biogas generation as well as higher COD reduction. A biogas yield of 68.57 mL/g of volatile solids with a COD reduction of 43.17% was obtained during AD of HC-treated TWE in 2 L bioreactors with a 10% seed dosage. This was further enhanced when food-waste was added to the AD as an external carbon source, and biogas generation enhanced by 11.8-fold for HC-treated TWE. Similarly, Lee et al. [55] implemented HC to disintegrate the waste-activated sludge (WAS) to facilitate the anaerobic digestion process for enhanced methane production. A synergistic enhancement of 15.90% in the methane yield was obtained during the combined effect of HC along with alkaline pretreatment (NaOH). Certain other zero-emission fuels, such as hydrogen (H_2), are also of great interest and have already been looked upon for their effective synthesis from natural biomass, such as cheese whey via the HC-based method [56]. Table 4 summarizes the reported data of HC-mediated biofuel synthesis.

Table 4. HC-mediated biofuel synthesis.

Product	Feedstock	Reactor Type	Optimum Parameters	Yield (%)	Ref
Biodiesel	Waste cooking oil	Slit venturi	T (°C): 40; Inlet Pressure (bar): 3; O/Methyl acetate: 1:12; Catalyst: 1 wt% CH_3OK	90	[37]
	Waste cooking oil (palm Olein)	Orifice	T (°C): 60; Inlet Pressure (bar): 2; O/Methanol: 1:6; Catalyst: 1 wt% KOH	98.1	[38]
	Rubber seed oil	Orifice	T (°C): 55; Inlet Pressure (bar): 3; O/Methanol: 1:6; Catalyst: 1 wt% KOH	96.5	[40]
	Rubber seed oil	Orifice	T (°C): 50; Inlet Pressure (bar): 3; O/Methyl acetate: 1:14; Catalyst: 0.75 wt% CH_3KO	88	[41]
	Used frying oil	Orifice	T (°C): 60; Inlet Pressure (bar): 3; O/Methanol: 1:6; Catalyst: 1 wt% KOH	95	[42]
	Palm oil	Rotor-stator	T (°C): 55; Methanol/O: 13% *v*/*v*; Catalyst: 3.67 g/L NaOH	99	[43]
	Waste and fresh cooking oil (sunflower)	Spinning tube	T (°C): 50; RPM: 1200-3500; O/Methanol: 1:12; Catalyst: 3 wt% KOH	97; 92.3	[44]
	Waste frying oil	Venturi	T (°C): 63; Inlet Pressure (bar): 3.27; O/Methanol: 1:6; Catalyst: 1.1 wt% NaOH	97.56	[45]
	Waste cooking oil	Orifice	T (°C): 35 ± 3; Inlet Pressure (bar): 7; O/Methanol: 1:6.8; Catalyst: 1 wt% NaOH	99	[9]
Bioethanol	Reed	Orifice	T (°C): 77; Inlet Pressure (atm): 5; S/L: 11.8% *wt*/*wt*; Base: 3% NaOH	90	[47]
	Sugarcane bagasse	Orifice	T (°C): 60; Inlet Pressure (bar): 3; S/L: 5; Base: 0.3 mol/L NaOH	96	[48]
Biogas	Wheat straw	Rotor-stator	T (°C): 37; RPM: 2500; S/L: 1.5% *wt*/*wt*; Base: 0.3 M KOH	-	[51]
	Agricultural biomass	Rotor-stator	Inlet Pressure (bar): 2	-	[52]
	Oily wastewater	Orifice	T (°C): 37 ± 1 Inlet Pressure (bar): 10.25	84.35	[53]
	Tannery waste effluent	Slit venturi	Inlet pressure (bar): 5; Seed dosages (wt%): 10	-	[54]
	Waste-activated sludge	Orifice	T (°C): 150; Up/down-stream pressure: 0.7, 0.07 MPa; Catalyst: 5 N NaOH	63.90	[55]
Hydrogen	Cheese whey	Orifice	Pressure (MPa): 0.7; Base: 5 M KOH	3.30 mol H_2/mol lactose	[56]

T: temperature; S/L: solid to liquid ratio.

7. Remediation

Due to the industrial revolution, a large number of harmful industrial dyes, pharmaceutical, and organic contaminants are contributing to environmental pollution, which are known for their toxic and bio-accumulative nature. There is mounting evidence on the link between pollutant exposure and human chronic diseases, such as cancer, diabetes, Parkinsons, and Alzheimers [57,58]. The complete elimination of recalcitrant pollutants is vital, but most of the pollutants are resistant towards conventional wastewater treatment technologies, such as biodegradation, adsorption, filtration, sedimentation, and chlorination. Even though membrane-based processes could effectively remove certain persistent pollutants, subsequent incineration is required to destroy the concentrated pollutant in a later phase. Therefore, a cost-effective one-step remediation process that can simultaneously mineralize the organic pollutant and disinfect harmful microorganisms without any additional step is of primary need. Global interest is rising in the implementation of advanced oxidation processes (AOPs), such as sonolysis, ozonation, and electrochemical-based water treatment methods. However, sonochemical and electrochemical-based treatments are not cost-effective for large-scale water systems. Cavitation-based AOP, such as hydrodynamic cavitation, could be a viable water treatment solution with a high potential impact on the operation cost. The mineralization of the pollutant via cavitation can be possible either by thermal decomposition at the inner or interfacial region of bubble or via radical attack in the bulk solution or at the bubble–liquid interfacial region. Cavitation is known to generate hydroxyl radicals ($OH^{\bullet}$) following the dissociation of water molecules (Equation (2)) and numerous reactive radical species [59] due to the cleavage of dissolved oxygen in the solution (Equations (3) and (4)).

$$H_2O \rightarrow H^{\bullet} + OH^{\bullet} \tag{2}$$

$$O_2 \overset{\ggg}{\rightarrow} 2^{\bullet}O^{\bullet} \tag{3}$$

$$^{\bullet}O^{\bullet} + H_2O \rightarrow 2^{\bullet}OH \tag{4}$$

HC has been utilized for wastewater remediation, and is, hence receiving unprecedented attention. Numerous reports on the removal of persistent organic pollutants, pharmaceuticals, dyes, cyanobacteria, viruses, bacteria, and microalgae have demonstrated its successful application.

7.1. *Pharmaceuticals*

Fate and health risks associated with environmentally persistent pharmaceutical pollutants are one of the major challenges of this century. Concerning the growing pharmaceutical industries and human consumption of pharmaceutical products, the environmental concentration of harmful pollutants is also increasing. The routes of exposure to the environment could originate from households, hospitals, and animal excretion. Pharmaceuticals are classified based on their therapeutic uses; for example, non-steroidal anti-inflammatory drugs (NSAIDs) such as Ibuprofen (IBP) and Diclofenac (DCF). Moreover, Diclofenac, 17b-estradiol, and 17a-ethinylestradiol are included under the EU priority substances list [60], and numerous other residues are expected to be included in the future. Several reports have indicated the presence of pharmaceuticals in freshwater bodies, out of which certain rivers are the prime source of drinking water [61]. Even though care has been taken in monitoring the presence of pharmaceuticals in surface water, limited water treatment methods are adopted to eliminate several pollutants. Also, pharmaceuticals such as Diclofenac, Carbamazepine, and Clofibric acid are recalcitrant towards biological remediation, which requires an alternative treatment method. There is ample evidence on the link of exposure to pharmaceutical pollutants and associated genetic, developmental, immune, and hormonal health effects [62]. HC and HC-based hybrid methods are found to be efficient for mineralizing these pollutants present in wastewater. Bagal and Gogate [63] studied the degradation of diclofenac sodium from water using the combined HC, H_2O_2, and photocatalytic process with TiO_2 as a catalyst. The extent of degradation was 26.85% using HC alone with circular venturi as a cavitating device after 2 h of operation, and this was increased to 95% when HC was combined with H_2O_2 (0.2 g/L), and photocatalytic oxidation with 0.2 g/L of TiO_2 catalyst. The combined processes were found to be more efficient than the individual processes, as more hydroxyl radicals (OH) were formed during the combined processes and thereby resulted in an enhanced rate of degradation. The synergistic coefficient was 2.5 for the combined process of HC/H_2O_2/photocatalytic oxidation, which indicates the synergetic effect of these combined processes. Thanekar et al. [64] studied the degradation of carbamazepine (CBZ), an anticonvulsant drug used for the treatment of epilepsy and neuropathic pain using a combination of HC and AOP. HC alone produced 38.7% degradation of CBZ at 4 bar inlet pressure using slit venturi as a cavitating device. This was further enhanced to 100% when HC was combined with H_2O_2 (CBZ:H_2O_2 = 1:5) and ozone (400 mg/h), and a synergistic coefficient of 3.2 was obtained for the combined process. Similarly, Wang et al. [65] reported the degradation of Tetracycline drug, which is an antibiotic used to treat bacterial infections in the human body, using a circular venturi-based HC process. HC alone caused 12.2% degradation of Tetracycline in 90 min, whereas it increased to 78.25% when HC was combined with photocatalytic oxidation (100 mg/L of

TiO_2). The agglomeration of TiO_2 was seen to be greatly prevented via cavitational effect, which was confirmed by scanning electron microscopy (SEM) analysis.

Rajoriya et al. [66] successfully integrated HC with a TiO_2 photocatalyst (samarium and nitrogen-doped) for the degradation of 4-Acetamidophenol (4-AMP). The combination of photocatalytic oxidation with HC resulted in 91% degradation compared to only 50% degradation via photocatalytic treatment. Moreover, under optimum conditions, it was observed that the energy efficiency of the HC-photocatalytic approach was nine-times higher than the US-photocatalytic treatment. The synthesis of samarium (Sm)- and nitrogen (N)-doped TiO_2 photocatalysts was performed by sol–gel and ultrasound-assisted sol–gel process, with the analytical characterization from photoluminescence spectroscopy (PL), UV-diffuse reflectance spectroscopy (DRS), x-ray photoelectron spectroscopy (XPS), x-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), field emission scanning electron microscopy (FESEM), and energy-dispersive X-ray analysis (EDX). Also, LC-MS analysis was used to verify the formation of degradants during the treatment. Roy et al. [67] utilized HC along with heterogeneous Fenton (α-Fe_2O_3) and persulfate for the degradation of Sulfadiazine (SDZ). Under the optimum conditions of an initial concentration of SDZ (20 ppm), pH of 4, inlet pressure of 10 atm, H_2O_2 loading at 0.95 mL/L, catalyst α-Fe_2O_3 loading of 181.8 mg/L, and $Na_2S_2O_8$ at 348.5 mg/L, 81% degradation was obtained within 90 min of treatment. Moreover, the simultaneous removal of clofibric acid, ibuprofen, naproxen, ketoprofen, carbamazepine, and diclofenac residues from wastewater was investigated by Zupanc et al. [68], while implementing a novel shear-induced HC reactor. With appropriate optimization, the overall removal was 47%–86% within just 15 min of treatment. Through these studies, it can be concluded that the combined AOPs are better in terms of higher degradation rate, better energy efficiency, and synergistic effect since more OH radicals are being generated, which causes higher degradation efficiency.

7.2. Dyes

Dyes are known hazardous chemicals which are persistently present in the water bodies due to the discharge of wastewater coming from various industries, such as textile, dyes and pigment, paper and fabric printing, and paints. Water-containing dyes are very carcinogenic and hazardous to human health, and they are dark in color, which disturbs the aquatic life of the water bodies, as this blocks the penetration of sunlight. Dye molecules are mainly aromatic in structure and are hard to degrade by conventional biological processes, as well as other conventional treatment processes, such as adsorption, coagulation by chemical agents, and membrane filtration, which are not able to mineralize these molecules and can only separate them physically from the wastewater, which causes secondary load on the environment. In this regard, numerous efforts have been made by researchers to mineralize dyes using various advanced oxidation processes, among which HC in combination with other AOPs has proved to be efficient for the mineralization of dyes.

Rajoriya et al. [69] studied the degradation of Rhodamine 6G dye using HC coupled with other oxidative agents, such as H_2O_2 and ozone. They compared two cavitating devices, slit and circular venturi, based on the percentage degradation achieved. Almost 32% degradation of Rh6G was obtained using slit venturi as compared to 29% using circular venturi in 120 min at an inlet pressure of 5 bar. The slit venturi, due to its higher throat perimeter, produced a higher number of cavities, and the power dissipation per unit pass was higher in the case of slit venturi than circular venturi, which makes slit venturi more efficient for the degradation of Rh6G. The combination of HC with H_2O_2 and ozone produced 53.72% and 100% degradation of Rh6G, respectively. The degradation of Rh6G using HC was found to be dependent on the solution pH, and in the case of Rh6G, the maximum degradation was found at pH 10. The hydrophobicity of pollutants favors its transport to both the inner and interfacial regions of the cavity, resulting in a higher degradation rate. The hydrophobicity of Rh6G was seen to decline at acidic pH, due to the protonation of nitrogen in the secondary amine group of the xanthene ring, which resulted in lesser transport of dye molecules to the cavity, thereby demonstrating a lower degradation rate. In another study by Rajoriya et al. [70], they reported the degradation of reactive blue 13 dye (RB13) using HC and HC-based hybrid processes. They compared various cavitating devices and concluded that the degradation efficiency of HC increases as the throat perimeter of the cavitating device increases. Furthermore, it has also been observed that venturi-based devices produce higher degradation efficiency than orifice plates, and slit venturi give higher degradation (47%) than all other devices. Operating HC, in combination with ozone, resulted in 100% decolorization with a 72% reduction in the total carbon content (TOC) of the RB13 solution. Bethi et al. [71] studied the degradation of crystal violet dye in aqueous solution using circular venturi-based HC and HC combined with photocatalytic oxidation. HC alone caused 45% degradation of the dye, whereas it increased to 98% when HC was combined with photocatalytic oxidation (0.6 g/L of Fe-TiO_2). Caliskan et al. [72] studied the degradation of reactive red 180 dye using a hybrid process of HC and photocatalysis (ZnO and TiO_2). The HC reactor was a circular venturi, and the combined process (HC + UV + ZnO) caused 99.7% color removal in 90 min, as compared to only 5% using HC alone. Similarly, various dyes, such as Rhodamine B [73], Reactive red 120 [7], Acid red 88 [74], Orange acid-II [75], Reactive orange 4 [76], and Methylene blue [77], have been successfully degraded in water using HC and HC-based hybrid processes.

All these studies have indicated that HC alone may not be sufficiently effective for the degradation of dyes, but its combination with other AOPs produces a strong synergistic effect. In the case of the HC process, venturi-based devices have been found to be more efficient for the degradation of dyes, as the quantum of cavities being generated and the number of OH radicals inside the venturi device are higher than in an orifice plate. It has also been found that devices with a higher throat perimeter for a given throat area maximize the number of cavities being generated, and therefore, such devices produce a higher degradation efficiency.

7.3. Pesticides and Insecticides

With the increasing demand for food grains and agriculture-based food products, farmers are using insecticides and pesticides to control the growth of insects. However, this causes contamination of farmland, and due to rainfall and excessive irrigation, they can be quickly transported to nearby water bodies to contaminate groundwater and freshwater supplies over a large geographical area. The contamination of surface and groundwater can have acute and chronic health effects on humans, as they are toxic and carcinogenic. These molecules are bio-refractory, and therefore can remain in the soil and water bodies for a prolonged time. During recent years, AOPs were found to be one of the most promising ways for the effective degradation of many organic pollutants, such as pesticides, and HC-based hybrid processes are extensively studied for this purpose, as they are energy-efficient and can be scaled-up.

Raut-Jadhav et al. [78] studied the degradation of imidacloprid (a systemic chloronicotinoid insecticide) in aqueous solutions using the combination of HC with various other advanced oxidation processes, such as Fenton, photo-Fenton, photolytic, and photocatalytic processes. The maximum degradation of 26% was obtained in 120 min using HC alone when circular venturi with a throat diameter of 2 mm was operated at an inlet pressure of 15 bar, and the solution pH was 2. This was further enhanced to 97.77%, 99.23%, 45.56%, and 55.18% when HC was combined with Fenton, photo-Fenton, photolytic, and photocatalytic processes, respectively, and the synergistic coefficient was found to be 3.636, 2.912, 0.82, and 0.92, respectively, for these combined processes. The most efficient hybrid process was HC + Fenton. Methomyl is another pesticide which is highly toxic to humans, livestock, pets, and wildlife, and has been degraded successfully using HC and its combination with intensifying agents, such as H_2O_2, Fenton reagent, and ozone [79]. The degradation rate of methomyl was 27.49% using HC at an inlet pressure of 3 bar in 120 min. The combination HC with H_2O_2 (molar ratio of methomyl to H_2O_2 as 1:30), Fenton oxidation ($FeSO_4$:H_2O_2 = 1:20), ozonation (ozone flow rate, 0.75 g/h) caused almost 100% degradation with a synergistic coefficient of 5.8, 13.41, and 47.6, respectively. Barik and Gogate [80] studied the degradation of 2,4,6-trichlorophenol (2,4,6-TCP) using HC, HC + H_2O_2, HC + O_3, and HC + H_2O_2 + O_3. The percentage degradation of 2,4,6-TCP was 32.13%, 62%, and 97.1% using HC, HC + H_2O_2, and HC + O_3, respectively, at an inlet pressure of 4 bar, H_2O_2 molar ratio of 1:5, and ozone flow rate of 400 mg/h. The synergistic coefficient for the combined process of HC + H_2O_2 and HC + O_3 was found to be 1.8 and 1.48, respectively. They also compared slit venturi with an orifice plate of the same throat area and found that HC with slit venturi as a cavitating device is more energy efficient in comparison to the orifice plate. This is due to venturies having smooth convergent and divergent sections, and therefore cavities do not collapse immediately, unlike the case of orifice plates, where pressure reverses immediately. Due to the smooth pressure recovery in the case of venturi, the life of cavities increases, and therefore, pollutant molecules could be exposed to the cavitation conditions for a long time, which causes higher degradation of pollutants. On the other hand, venturies are also better in terms of energy efficiency, as higher flow rates are obtained in the case of venturi than orifice plate for a given pressure drop.

Triazophos is generally used as an insecticide on various crops, such as cotton and rice, to control aphids, fruit borers, leaf hoppers, and cutworms. Recent metabolic studies conducted on various animals, such as mice, rats, dogs, and pigs, indicated that triazophos dose in the range of 26–82 mg/kg body weight causes sudden death and leads to the development of cancer tumors in these animals. Due to these reasons, WHO considers triazophos as a highly hazardous compound, and one of the principal manufacturers has suspended the production and sales of this insecticide, but still, in many countries, it is being used as an insecticide. Recently, Gogate and Patil [81] studied the degradation of Triazophos using HC and HC-based hybrid methods. They employed different combinations of HC with Fenton oxidation, ozonation, photocatalytic oxidation, and hydrogen peroxide. The maximum degradation of 35.77% was obtained using an orifice plate with a throat diameter of 2 mm operating at an inlet pressure of 5 bar. Beyond this operating pressure, the percentage degradation decreased with an increase in pressure due to the onset of choked cavitation, where a cavity cloud is formed instead of a single cavity. In the case of HC, it is essential to note that HC processes should be operated above the choked cavitation number to get the maximum degradation rate. About 82.2% degradation of triazophos was achieved by the combination of HC and Fenton's oxidation ($FeSO_4$: H_2O_2 = 2:2), whereas 86.68% degradation was achieved using the combination of HC and ozonation (ozone flow rate, 0.576 g/h). Patil et al. [82] adopted the combined approach of HC along with Fenton's reagent and with H_2O_2 for the degradation of imidacloprid pesticide. A faster and complete degradation was obtained under optimum conditions and with the combined effect of HC and Fenton's within just 60 min of treatment in comparison to 120 min under HC/H_2O_2 treatment. Joshi et al. [83] utilized HC and Fenton's reagent for the removal of dichlorvos pesticide and under optimum conditions of pH, solution temperature, HC inlet pressure, and loading of Fenton's reagent, 91.5% degradation in 1 h was possible.

7.4. Other Organic Compounds

2,4-dinitrophenol (DNP) is known as a starting material for pesticide, herbicide, as well as dye production, and is recognized for its toxic effects. The removal of DNP was investigated by Bagal et al. [84] under various combined processes, i.e., HC/H_2O_2, HC/$Na_2S_2O_8$/$FeSO_4$, HC/$FeSO_4$/H_2O_2, HC/Fe/H_2O_2, and HC/CuO/H_2O_2. The complete degradation was achieved under the combination of HC/Fenton ($FeSO_4$/H_2O_2) process within 60 min of treatment. Barik et al. [85] verified the HC-based combined approach (HC/UV, HC/O_3, HC/UV/O_3) for the degradation of 4-chloro-2-aminophenol (4C2AP). A degradation of up to 96.85% was achieved under HC/UV/O_3, following optimum conditions of inlet pressure (4 bar), pH (6), and reaction temperature (30 °C). Similarly, Jawale et al. [86] adopted the combined process of HC, along with O_3 and a catalyst (TiO_2/ZnO/CuO), for the degradation of potassium thiocyanate (KSCN) present in the wastewater. The complete degradation of KSCN was obtained via the combination of HC/H_2O_2/O_3/CuO, whereas maximum degradation of 86.5% could be achieved via HC/O_3/CuO. First-time application of the HC/persulfate (PS) process was implemented in the removal of Bisphenol A (BPA) [87]. With the increase in PS loading and solution temperature, the degradation rate constant increased. The formation of five intermediates over 120 min of treatment was confirmed by LC-MS analysis, and the mineralization efficiency (76.92%) was monitored via TOC analyzer.

7.5. Bacteria and Aquatic Organisms

Pathogenic organisms, such as bacteria and viruses, could result in fatal diseases, such as typhoid, cholera, leprosy, polio, pneumonia, hepatitis, and tuberculosis. In this aspect, the disinfection of potable water and wastewater can provide better health prospects. Even though there are several disinfection methods, such as UV, ozone, and chlorination, they are either not feasible for large scale implementation or not universally applicable. Disinfection by HC is emerging as one of the best solutions available today. Jain et al. [88] demonstrated the inactivation of gram-negative *Escherichia coli* and gram-positive *Staphylococcus aureus* bacteria via HC under a vortex diode and orifice-type cavitating device. After 1 h of treatment under vortex diode configuration, a complete elimination of *E. coli* was achieved (99%) at a pressure drop of 0.5 bar, whereas 98% removal of *S. aureus* was obtained at a higher pressure drop. However, with orifice-type devices, adequate disinfection can only be achieved at a higher inlet pressure such as 10 bar. The proposed disinfection mechanism includes oxidative damage to the cell wall and DNA denaturation. Similarly, the disinfection of gram-negative *Escherichia coli*, *Klebsiella pneumoniae*, *Pseudomonas syringae*, *Pseudomonas aeruginosa*, and gram-positive *Bacillus subtilis* was reported by Loraine et al. [89], demonstrating an effective removal of all the species. The cavitating jet technology ($D_{YNA}J_{ETS}$) opted for the disinfection via the HC method, where under an optimum nozzle pressure of 2.1 bar (C_v: 0.5), the disinfection of *E. coli* has shown five orders of magnitude reduction in its initial concentration. In general, a higher disinfection rate was witnessed for the gram-negative bacteria carrying thinner wall cells compared to gram-positive. Moreover, the $D_{YNA}J_{ETS}$ is 10–100-times more energy-efficient than an ultrasound-based disinfection process. In addition, recently, Sarc et al. [90] reported exploring certain new dimensions of cavitation formation, such as (super) cavitation via a venturi-type HC with a rotation generator that has effectively inactivated *Legionella pneumophila*, *Escherichia coli*, and *Bacillus subtilis*. Moreover, the disinfection capability of a green hybrid process utilizing HC along with natural clove oil was reported by Mane et al. [91], which was also able to eliminate gram-negative *E. coli* and gram-positive *S. aureus* bacteria. The removal of waterborne viruses, such as enteric viruses (Rotavirus, Norovirus, Astrovirus, Sapovirus, Adenovirus) and Hepatitis A, is highly required due to their harmful effects. The effort to introduce HC for the removal of harmful waterborne virus was accomplished by Kosel et al. [92], where a norovirus surrogate *Bacteriophage MS2* was subjected to the treatment. It was assumed that the generated OH radicals are responsible for damaging the host's recognition receptors present on the surface of *Bacteriophage MS2*, which leads to the reduction in viral infectivity of more than 4 logs.

Cyanobacteria (CB) or blue-green algae are omnipresent in natural water sources, and their respective bloom has drawn worldwide attention due to the adverse health effects. A significant portion of cyanobacterial species is known to produce toxins (cyanotoxin), which can lead to hepatotoxicity, neurotoxicity, and dermatotoxicity, and could even be carcinogenic for humans [93]. Worldwide reports have documented the death of birds, dogs, as well as other domestic animals via the consumption of cyanobacterial bloom-contaminated surface water. Following fisheries, the paralytic shellfish toxins (Saxitoxin family) are well-known for their detrimental effects. Public drinking water systems, as well as fisheries, are prone to the contamination of cyanotoxins, and hence a complete elimination of cyanotoxins from the respective water bodies is vital. Conventional treatment technologies, such as chlorination, coagulation, sand filtration, and activated carbon, can either remove a small fraction of the toxin or are incapable of removing the broad range of cyanotoxins. Even though membrane-based processes could effectively remove intracellular toxins, they are ineffective for the extracellular removal of toxins [94]. AOPs such as sonolysis, UV, ozonation, and electrochemical methods were implemented for the removal of cyanotoxins. However, UV irradiation is only valid at an impractically high dose, whereas ozone-based oxidation can result in lysing intact algal cells and thereby rereleasing toxins [95]. On the other hand, sonochemical-based treatment is not cost-effective to be utilized for large-scale drinking water systems or fisheries. Therefore, a cost-effective water treatment process, for example, HC, is the primary need that can remove the cyanobacterial family without cell lysis and can also degrade the generated cyanotoxins. Li et al. [96] demonstrated the effective removal of blue-green algae (i.e., cyanobacteria) by HC-based treatment. The free radicals produced via HC destroyed the algal cells by disrupting cellular constituents, along with lipid peroxidation of algal membranes. The peroxidation product, i.e., malondialdehyde (MDA), was monitored via heating the acidic solution in the presence of thiobarbituric acid (TBA) and measuring the resultant pink color at 532 nm. The MDA content was seen to increase remarkably with HC treatment duration until 10 min, demonstrating the successful radical generation as well as lipid peroxidation of *Microcystis aeruginosa*. Moreover, the comparison between HC and ultrasound treatment revealed that there was an algal reduction of 93% during HC compared to only 61% via sonication. The change in the cell morphology before and after the treatment was examined via scanning electron microscopy (SEM), and a phytoplankton analyzer was used to measure the photosynthetic activity. Overall, the inactivation mechanism of cyanobacteria *M. aeruginosa* includes the disruption of the cell wall, membrane, and gas vacuoles, and interference in the photosynthetic activity. Similarly, the combination of HC and ozonation was adopted by Wu et al. [97] for the removal of *Microcystis aeruginosa*. Regarding the operational parameters, the algal removal percentage was seen to decline with a rise in the reaction solution temperature beyond 20 °C and with a decline in the orifice diameter. A synergistic enhancement in the algal removal of up to 99% was achieved only under the combined effect of HC and ozone. The cavitational effect could have enhanced both the rate of ozone penetration into the aqueous solution and algal cells, making it more susceptible to oxidative stress as well as radical-driven cell rupture.

Individual aquatic organisms such as rotifers can be harmful for humans and are also known to be detrimental for microalgae cultivation in open ponds. Kim et al. [98] examined the role of HC on rotifer *Brachionus rotundiformis* presence in microalgae open ponds and on the reproductive capability of green microalgae *Nannochloropsis salina* (dropped by 12–15%). The rotifer removal efficiency was found to be dependent on the number of HC passes, demonstrating almost complete removal after four passes. Qualitative analysis via microscopic observation revealed that adult rotifers are more prone to damage via HC rather than the eggs. While the outer membrane and organelles of adult rotifers were entirely detached, only a few eggs received minor cracks on their surface. Cvetković et al. [99] also investigated the pilot-scale HC treatment of ballast water containing aquatic organisms such as zooplankton *copepods*, and *Artemia salina* cysts. Under controlled mesocosm conditions, both organisms received complete damage within just 60 min of treatment.

7.6. Industrial Effluent

All the studies, as discussed in the previous sections, only reported on the degradation of single pollutants in water using HC and HC-based hybrid processes, and the concentrations of these organic pollutants are in the range of 20–100 ppm. To scale-up the HC-based hybrid process, it is crucial to study the efficiency of these processes for the treatment of real industrial effluents. In this regard, recently, a few research studies have been reported on the treatment of industrial effluent using HC-based hybrid processes.

Wastewater from leather industries is a cause of concern in countries such as China, India, and Brazil, as they are the largest exporters of leather-based products. Moreover, the treatment of tannery waste effluents (TWE) is of a specific challenge owing to the presence of larger complex molecules. Hydrodynamic cavitation could be a viable option to treat TWE, which has also been reported in recent years. Alum coagulation along with HC followed by ultrasound (US) has been utilized as a pretreatment strategy for TWE treatment to mineralize the organic contents and to enhance the biodegradability of TWE to undergo anaerobic digestion (biodegradability index enhanced from 0.14 to 0.57) [100]. Moreover, the coagulation-HC was demonstrated to be six-times more energy-efficient than coagulation-US. In another study, Saxena et al. [101] reported that HC in combination with H_2O_2, O_3, and Fenton's reagent can be effectively used for the reduction in COD and TOC of the TWE, and these processes caused an increase in the biodegradability index (BI) of the treated TWE samples. The main objective of this study was to reduce the COD and TOC of the TWE samples and to enhance the BI value of the treated samples. For the good biodegradability of any wastewater, a minimum BI value of 0.3 is considered to be ideal for aerobic digestion, and a value of ≥0.4 is desirable for anaerobic digestion. They observed that HC alone caused 14.46% of COD reduction from the TWE samples at an optimum inlet pressure of 5 bar within 120 min, and BI value increased from 0.33 to 0.43. HC combined with Fenton's reagent was found to be the most efficient hybrid process for the treatment of TWE and a maximum reduction of 50.20% COD, and 32.41% TOC at an $FeSO_4.7H_2O/H_2O_2$ ratio of 1:3 (*w*/*w*) was obtained, and BI value increased to 0.46. The increased BI value indicates that HC and HC-based hybrid processes could disintegrate more recalcitrant organic molecules into biodegradable compounds, and therefore may be combined with anaerobic digestion for the overall efficiency enhancement of the combined HC and anaerobic digestion. Rajoriya et al. [102] reported on the treatment of the textile dyeing industry (TDI) effluent using HC and in combination with AOPs. They observed that HC alone is not very useful for the treatment of TDI effluent, as only 17% TOC and 12% COD reduction was obtained at an inlet pressure of 5 bar and pH of 6.8. However, the combined process of HC and Fenton's reagent was most effective, with 48% TOC and 38% COD reduction, as well as complete decolorization of the TDI effluent, whereas the combination of HC with oxygen (2 L/min) and ozone (3 g/h) reduced 48% TOC, 33% COD, and 48% TOC, 23% COD of TDI effluent, respectively. Boczkaj et al. [103] reported the degradation of wastewater obtained from the production of bitumens using HC and in combination with AOPs (O_3/H_2O_2/Peroxone). They reported that HC combined with ozone was the most effective treatment process, where 40% COD and 50% BOD reduction were observed. Other processes, such as HC + H_2O_2, HC + Peroxone, and HC alone were also investigated, and only 20%, 25%, and 13% reduction in COD and 49%, 32%, and 18% reduction in BOD were observed, respectively. This research revealed that most of the volatile organic compounds were effectively degraded using the combination of HC and AOPs. Similarly, Thanekar et al. [104] reported the treatment of real industrial effluent of a local industry containing phenolic derivatives, resins, and sodium acetate, which involved HC in combination with AOPs. HC alone provided only a 7.9% reduction in the COD at the optimized inlet pressure of 4 bar and pH 4. A maximum COD reduction of 60.8% was achieved using the combination of HC + H_2O_2 + O_3, whereas only 40.3%, 38.7%, and 8.5% reduction in COD were achieved using the combinations of HC + H_2O_2, HC + $O_{3,}$ and HC + persulphate, respectively.

All these studies conducted for the treatment of industrial effluents indicated that HC and HC-based hybrid methods can also effectively be used on a large scale and can be incorporated into the current conventional wastewater treatment plants for increasing their overall efficiency. If the HC process is used before the biological treatment processes, it can significantly enhance the COD reduction as well as improve the generation of biogas. Table 5 summarizes the data of HC-assisted remediation of toxic pollutants.

Table 5. HC-assisted remediation of toxic pollutants.

Category	Pollutant	HC Type	Parameters	Comment	Ref.
Pharmaceuticals	Diclofenac sodium	Slit venture (Flow area: 11.4 mm^2, α: 1.38, β: 0.052, Half divergence angle: 5.5°, Throat height to length ratio: 1:1)	Inlet Pressure (bar): 3, C_V: 0.28, Flow rate (LPH): 1075, Initial concentration (ppm): 20, Reaction volume (L): 5, Treatment time (min): 120, pH: 4, T (°C): 35, H_2O_2: 0.2 g/L, TiO_2: 0.2 g/L	**HC alone:** 26.85% degradation **HC+UV+TiO$_2$:** 94.78% degradation **Synergetic coefficient: 2.5**	[63]
	Carbamazepine (CBZ)	Slit venture (Flow area: 14.64 mm^2, α: 1.30, β: 0.038, Half divergence angle: 5.5, Throat height to length ratio: 1:1)	Inlet pressure (bar): 4; Initial concentration (ppm): 10, Reaction volume (L): 4, Treatment time (min): 120, pH: 4, T (°C): 35, H_2O_2 (ppm): 50, O_3 flow rate (g/h): 0.4	**HC alone:** 38.7% degradation **HC+H$_2$O$_2$+O$_3$:** 100% degradation **Synergetic coefficient: 3.2**	[64]
	Tetracycline	Circular venturi (Throat diameter: 2 mm, α: 2.00, Half divergence angle: 10°)	Inlet pressure (bar): 3.4, C_V: 0.59, Flow rate (LPH): 380.52, Initial concentration (ppm): 30, Reaction volume (L): 4, Treatment time (min): 90; pH: 4.2, T (°C): 30, UV (W): 9, TiO_2 (ppm): 100	**HC alone:** 12.2% degradation **HC+UV+TiO$_2$:** 78.2% degradation **Synergetic coefficient: 3.2**	[65]
	4-acetamidophenol	Slit venturi: (Flow area: 3.14 mm^2, α: 2.64, β: 0.011, Half divergence angle: 6.5 Throat height to length ratio: 1:1)	Inlet pressure (bar): 5, C_V: 0.07, Initial concentration (ppm): 50, Reaction volume (L): 3, Treatment time (min): 180, pH: 6.8, T (°C): 20–25, UV (W): 3, TiO_2: 2 g/L	**HC alone:** 8.3% degradation **HC+UV+TiO$_2$:** 90.8% degradation **Synergetic coefficient: 1.5**	[66]
	Sulfadiazine	Circular orifice: (Hole diameter: 4 mm, Flow area: 25.12 mm^2, α: 1 mm^2, β: 0.073)	Inlet pressure (atm): 10, C_V: 0.25, Initial concentration (ppm): 20, Reaction volume (L): 5, pH: 4, Treatment time (min): 90, H_2O_2: 0.95 mL/L, α-Fe_2O_3 (ppm): 181.8, $Na_2S_2O_8$: 348.5 mg/L	**HC+Fenton+Persulfate:** 81% degradation	[67]
	Clofibric acid; Ibuprofen; Naproxen; Ketoprofen; Carbamazepine; Diclofenac	Rotor-stator: (R1: rotor with 12 grooves, R2: rotor with 11 grooves)	Initial concentration: 1 μg/L; Reaction volume (L): 2.5; T (°C): 50; Treatment time (min): 15; H_2O_2: 1.7 g/L	**HC+H$_2$O$_2$:** 55%–93% removal	[68]

Table 5. *Cont.*

Category	Pollutant	HC Type	Parameters	Comment	Ref.
Dyes	Rhodamine 6G (Rh6G)	Slit venturi: (Flow area: 3.14 mm^2, α: 2.64, β: 0.011, Half divergence angle: 6.5 Throat height to length ratio: 1:1)	Inlet pressure (bar): 5, C_V: 0.07, Flow rate (LPH): 1.64 × 10^{-4} m^3/s, Initial concentration (ppm): 50, Reaction volume (L): 6, Treatment time (min): 120, pH: 10, T (°C): 30 ± 2, O_3 flow rate (g/h): 3	**HC alone:** 32% decolorization **HC+H_2O_2:** 53.72% decolorization **HC+O_3:** 100% decolorization/73% mineralization **Synergetic coefficient: 1.58**	[69]
	Reactive blue 13	Slit venturi: (Flow area: 3.14 mm^2, α: 2.64, β: 0.011, Half divergence angle: 6.5, Throat height to length ratio: 1:1)	Inlet pressure (bar): 4, C_V: 0.08, Initial concentration (ppm): 30, Reaction volume (L): 6, Treatment time (min): 120, pH: 2.0, O_3 flow rate (g/h): 3	**HC alone:** 47% decolorization **HC+O_3:** 100% decolorization/72% mineralization **Synergetic coefficient: 3.47**	[70]
	Crystal violet	Circular venturi: (Throat diameter: 2 mm, α: 2.00, β: 0.013 Half divergence angle: 6°)	Inlet pressure (bar): 5, C_V: 0.15, Initial concentration (ppm): 50, Reaction volume (L): 5, Treatment time (min): 90, pH: 6.5, T (°C): 35, **Fe-TiO_2** (ppm): 600, UV (W): 125	**HC alone:** 44.5% decolorization **HC+UV+Fe-TiO_2:** 98% decolorization	[71]
	Reactive red 180	Circular venturi: (Throat diameter: 7 mm, α: 0.57, β: 0.05, Half divergence angle: 6°)	Inlet pressure (bar): 5, C_V: 0.177, Flow rate: 4.1 m^3/h, Initial concentration (ppm): 100, Reaction volume (L): 16, Treatment time (min): 180, pH: 2, T (°C): 35, UV (W): 15 (6 lamps)	**HC alone:** 4.6% decolorization **HC+UV+TiO_2:** 90.7% decolorization/45% COD/38.7% TOC removal **HC+UV+ZnO:** 99.7% decolorization/77% COD/66% TOC removal **Synergetic coefficient: 1.8**	[72]
	Rhodamine-B	Circular venturi: (Throat diameter: 2 mm, α: 2.0, β: 0.027, Half divergence angle: 6.4°)	Inlet pressure (bar): 5, C_V: 0.091, Flow rate: 400 L/h, Initial concentration (ppm): 10, Reaction volume (L): 4, Treatment time (min): 120, pH: 2.5, T (°C): 40, $FeSO_4$:H_2O_2: 1:5	**HC alone:** 59.3% degradation/30% TOC removal **HC+ Fenton:** 99% degradation/57% TOC removal	[73]
	Acid Red 88	Circular venturi: (Throat diameter: 2 mm, α: 2.0, β: 0.013 Half divergence angle: 6.4°)	Inlet pressure (bar): 5, C_V: 0.15, Flow rate (LPH): 410, Initial concentration (µM): 100, Reaction volume (L): 4, Treatment time (min): 120, pH: 2, T (°C): 35, Molar ratio (dye: H_2O_2): 1:60	**HC alone:** 92% decolorization/35% TOC removal **H_2O_2 alone:** 4.6% decolorization **HC+ H_2O_2:** 99% decolorization/72% TOC removal	[74]

Table 5. *Cont.*

Category	Pollutant	HC Type	Parameters	Comment	Ref.
	Reactive red 120	Circular venturi: (Throat diameter: 2 mm, α: 2.0, β: 0.013, Half divergence angle: 6.4°)	Inlet pressure (bar): 5, C_V: 0.15, Flow rate (LPH): 410, Initial concentration (ppm): 50, Reaction volume (L): 6, Treatment time (min): 180, pH: 2, T (°C): 35, Molar ratio (dye: H_2O_2): 1:60	**HC alone:** 60% decolorization/28% TOC removal **H_2O_2 alone:** 13% decolorization **HC+ H_2O_2:** 100% decolorization & 60% TOC removal	[7]
	Orange acid-II (OA-II)	Circular orifice: (Throat diameter: 2 mm, α: 2, β: 0.0064)	Inlet pressure (bar): 5, Initial concentration (ppm): 20, Reaction volume (L): 4, Treatment time (min): 120, pH: 3, T (°C): 20, H_2O_2 (ppm): 571.2	**HC alone:** 34.2% decolorization/27.3% TOC reduction **H_2O_2 alone:** 11% decolorization **HC+ H_2O_2:** 96% decolorization	[75]
	Reactive orange 4	Circular venturi: (Throat diameter: 2 mm, α: 2.00, β: 0.013, Half divergence angle: 6.4°)	Inlet pressure (bar): 5, C_V: 0.15, Flow rate (LPH): 410, Initial concentration (ppm): 40, Reaction volume (L): 5, Treatment time (min): 120; pH: 2, Molar ratio: 1:30 (dye: H_2O_2), O_3 flow rate (g/h): 3	**HC alone:** 37.23% decolorization **H_2O_2 alone:** 4.65% decolorization **HC+ H_2O_2+O_3:** 100% decolorization **Synergetic coefficient: 3.87**	[76]
	Methylene blue	Circular venturi: (Throat diameter: 2 mm, α: 2.0, β: 0.013, Half divergence angle: 6.4°)	Inlet pressure (bar): 5, C_V: 0.15, Flow rate (LPH): 410, Initial concentration (ppm): 50, Reaction volume (L): 5, Treatment time (min): 120; pH: 2, T (°C): 35, UV (W): 125, Bismuth doped TiO_2 (**Bi-TiO_2**) (ppm): 200	**HC alone:** 32.32% decolorization **UV+Bi-TiO_2:** 26.52% decolorization **HC+UV+Bi-TiO_2:** 64.5% decolorization **Synergetic coefficient: 1.46**	[77]
Pesticides	Imidacloprid	Circular venturi: (Throat diameter: 2 mm, α: 2.0, β: 0.013, Half divergence angle: 6.4°)	Inlet pressure (bar): 15, C_V: 0.067, Flow rate: 610 L/h, Initial concentration (ppm): 25, Reaction volume (L): 5, pH: 2.7, T (°C): 31, Molar ratio: 1:40 (pollutant: H_2O_2), UV (W): 250, Nb_2O_5 (ppm): 200	**HC alone:** 26% degradation (120 min)/9.6% mineralization (180 min) **HC+Fenton:** 97.77% degradation (15 min) **HC+UV+Nb_2O_5:** 55% degradation in (120 min)/19% Mineralization (180 min) **HC+photo-Fenton:** 99.23% degradation (15 min) **Synergetic coefficient: 2.912**	[78]

Table 5. *Cont.*

Category	Pollutant	HC Type	Parameters	Comment	Ref.
	Methomyl	Circular venturi: (Throat diameter: 2 mm, α: 2.0, β: 0.013, Half divergence angle: 6.4°)	Inlet pressure (bar): 5, C_V: 0.21, Flow rate: 375 L/h, Initial concentration (ppm): 25, Reaction volume (L): 5, pH: 2.5, Molar ratio (pollutant: H_2O_2): 1:30, Molar ratio ($FeSO_4$: H_2O_2): 1:20, O_3 flow rate (g/h): 0.75	**HC alone:** 27.49% degradation (120 min) **O_3 alone:** 6% mineralization (120 min) **HC+ H_2O_2:** 97.2% degradation (60 min)/15.4% TOC reduction (120 min) **Fenton alone:** 29% degradation (30 min)/9.5% TOC reduction (120 min) **HC+ Fenton:** 100% degradation (30 min)/35.8% TOC reduction (120 min) **HC+O_3:** 100% degradation/70.8% TOC reduction (120 min) **Synergetic coefficient: 47.6**	[79]
	2,4,6- Trichlorophenol (2,4,6-TCP)	Slit venturi: (Flow area: 11.4 mm^2, α: 1.38, β: 0.052, Half divergence angle: 5.5°, Throat height to length ratio: 1:1)	Inlet pressure (bar): 4, C_V: 0.23, Initial concentration (ppm): 20, Reaction volume (L): 7, Treatment time (min): 120, pH: 7, T (°C): 30, Molar ratio: 1:5 (TCP: H_2O_2), O_3 flow rate (g/h): 0.4	**HC alone:** 32.13% degradation **HC+ H_2O_2:** 62% degradation **HC+O_3:** 97.1% degradation **Synergetic coefficient: 1.48**	[80]
	Triazophos	Circular orifice: (Throat diameter: 2 mm, α: 2.0, β: 0.0064)	Inlet pressure (bar): 5, C_V: 0.29, Initial concentration (ppm): 20, Reaction volume (L): 4, Treatment time (min): 120, pH: 3, O_3 flow rate (g/h): 0.576, ($FeSO_4$:H_2O_2): 2:2	**HC alone:** 35.77% degradation **HC+Fenton:** 82.2% degradation **Synergetic coefficient: 3.34**	[81]
	Imidacloprid	Slit venturi: (Throat dimensions: W: 7.67 mm, H: 1.91 mm, L: 1.91 mm, Half divergence angle: 5.5°)	Inlet pressure (bar): 4, Initial concentration (ppm): 20, Reaction volume (L): 4, Treatment time (min): 60, pH: 3, T (°C): 34, (H_2O_2: Fe powder): 2:1	**HC alone:** 27.93% degradation **HC+Fenton:** 100% degradation	[82]
	Dichlorvos	Circular orifice: (Throat diameter: 2 mm)	Inlet pressure (bar): 5, Initial concentration (ppm): 20, Reaction volume (L): 4, Treatment time (min): 60, pH: 3, T (°C): 31, H_2O_2 (ppm): 16, $FeSO_4$ (ppm): 48	**HC alone:** 12.5% degradation **HC+Fenton:** 91.5% degradation	[83]

Table 5. *Cont.*

Category	Pollutant	HC Type	Parameters	Comment	Ref.
Organic pollutants	2,4-dinitrophenol	Circular orifice: (Throat diameter: 2 mm)	Inlet pressure (bar): 4, Initial concentration (ppm): 20, Reaction volume (L): 4, Treatment time (min): 60, pH: 4, T (°C): 35, H_2O_2 (g/L): 0.3, $FeSO_4$ (g/L): 0.6	**HC alone:** 12.4% degradation **HC+ Fenton:** 100% degradation	[84]
	4-chloro 2-aminophenol	Circular orifice: (Throat diameter: 2 mm)	Inlet pressure (bar): 4, Initial concentration (ppm): 20, Reaction volume (L): 7, Treatment time (min): 120, pH: 6, T (°C): 30, UV (W): 8, O_3 flow rate (mg/h): 400	**HC only:** 21.89% degradation **O_3 only:** 64.29% degradation **UV only:** 68.89% degradation **HC+UV+O_3:** 96.85% degradation	[85]
	Potassium thiocyanate	Circular venturi: (Throat diameter: 2 mm)	Inlet pressure (bar): 4, C_V: 0.205, Flow rate (LPH): 339, Initial concentration (ppm): 20, Reaction volume (L): 4, Treatment time (min): 120, pH: 2, T (°C): 37, H_2O_2 (ppm): 20, O_3 flow rate (mg/h): 400, CuO (g/L): 0.15	**HC only:** 52.8% degradation **H_2O_2 only:** 6.7% degradation **O_3 only:** 5.6% degradation **CuO only:** 5.1% degradation **HC+H_2O_2+O_3+ CuO:** 100% degradation	[86]
	Bisphenol A	Circular orifice: (Throat diameter: 2 mm)	Inlet pressure (MPa): 0.5, Initial concentration (ppm): 10, Reaction volume (L): 10, Treatment time (min): 120; pH: 6, T (°C): 50; PS: 4.17 mM	**HC+ Persulfate (PS):** 81.28% degradation	[87]
Bacteria	Gram-negative: Escherichia coli; Gram-positive: Staphylococcus aureus	Vortex diode: (Chamber diameter: 66 mm)	Pressure drop (bar): 0.5, Reaction volume (L): 20	99% and 98% removal, respectively	[88]
	Gram-negative: Escherichia coli; Klebsiella pneumoniae; Pseudomonas syringae; Pseudomonas aeruginosa; Gram-positive: Bacillus subtilis	DynaJets Nozzle	Nozle pressure (bar): 2.1, Reaction volume (L): 1.8–20	Highly efficient overall inactivation	[89]

Table 5. *Cont.*

Category	Pollutant	HC Type	Parameters	Comment	Ref.
	Gram-negative: Legionella pneumophila; Escherichia coli; Gram-positive: Bacillus subtilis	Circular venturi: (Throat cross-section: 1 × 5 mm, Half divergence angle: 5°)	Inlet pressure (bar): 0.2, C_V: 0.78, Flow rate (L/min): 0.2, Reaction volume (L): 4, Treatment time (min): 120	Complete inactivation	[90]
	Gram-negative: Escherichia coli; Gram-positive: Staphylococcus aureus	Vortex diode: (Chamber diameter: 66 mm)	Pressure drop (bar): 2, Reaction volume (L): 20	100% disinfection	[91]
Virus	Bacteriophage MS2	Circular orifice: (Throat diameter: 2 mm)	Inlet pressure (bar): 7, Reaction volume (L): 1, Treatment time (min): 90, T (°C): <29	Infectivity reduced to 4 logs (≥99.99%)	[92]
Cyanobacteria	Microcystis aeruginosa	Circular orifice	Inlet pressure (MPa): 0.4, Reaction volume (L): 5, Treatment time (min): 30, T (°C): 25, H_2O_2: 0.1 mmol/L	**HC+ H_2O_2:** 93% algal removal	[96]
	Microcystis aeruginosa	Circular orifice: (Throat diameter: 5, 10, or 12 mm)	Initial concentration: 30 µg/L, Reaction volume (L): 1.75, Treatment time (min): 10, T (°C): 20, O_3 flow rate (mg/min): 1.9	**HC alone:** 15% algal removal **O_3 alone:** 35% algal removal **HC+O_3:** 99% algal removal	[97]
Aquatic organisms	Rotifer: Brachionus rotundiformis	Circular orifice: (Throat diameter: 0.5 mm, 27 holes)	Initial concentration: 1000–8000 individuals/mL, Inlet pressure (bar): 3, Reaction volume (L): 20	99.9% removal	[98]
	Multicellular: Copepod; Unicellular: Natural bacteria; Cyst: Artemia salina	Circular orifice	Inlet pressure (bar): 1.8–2.8, Reaction volume (L): 150, Treatment time (min): 60	100%, 86%, and 99.8% damage, respectively	[99]
Industrial effluent	Tannery waste effluent (TWE)	Slit venturi: (Flow area: 3.14 mm^2, α: 2.64, β: 0.011, Half divergence angle: 6.5, Throat height to length ratio: 1:1)	Inlet pressure (bar): 5, Initial COD (ppm): 8800–10,080, TOC (ppm): 2290–2583, BOD (ppm): 2800–3200, BI: 0.28–0.33	**HC:** 14.46% COD & 12.60% TOC reduction, BI: 0.43 **HC+ O_3:** 26.81% COD reduction at 7 g/h of ozone feed, BI: 0.42 **HC+H_2O_2:** 34.35% COD reduction at H_2O_2 feed rate of 14.27 g/L, BI: 0.41 **HC+Fenton:** 50.20% COD reduction at Fenton's dose of 3.0 g/L and $FeSO_4.7H_2O$: H_2O_2 of 1:3, BI: 0.46, **Synergetic coefficient: 2.68**	[100]

Table 5. *Cont.*

Category	Pollutant	HC Type	Parameters	Comment	Ref.
	Tannery waste effluent organic content	Slit venturi: (Throat area: 3.14 mm^2)	Inlet pressure (bar): 5, Treatment time (min): 120, Reaction volume (L): 20, pH: 4.5, T (°C): 30 ± 2; Alum dose: 0.5 g/100 mL, 2 g/100 mL	**HC+Coagulant:** 35.6% COD and 43.9% TOC reduction, BI increased from 0.14 to 0.57	[101]
	Textile dyeing industry (TDI)	Slit venturi: (Flow area: 3.14 mm^2, α: 2.64, β: 0.011, Half divergence angle: 6.5, Throat height to length ratio: 1:1)	Inlet pressure (bar): 5, COD (ppm): 2560–4640, TOC (ppm): 556–1184	**HC:** 12% COD reduction, 17% TOC reduction **HC+O$_3$:** 48% TOC, 22.72% COD reduction at ozone flow rate of 3g/h, **Synergetic coefficient: 1.42** **HC+Fenton:** 48% TOC, 38% COD reduction at $FeSO_4.7H_2O$:H_2O_2 of 1:5, **Synergetic coefficient: 1.42**	[102]
	Industrial effluent from bitumen production process industry	Circular venturi: (Throat diameter: 2 mm, α: 2.00, β: 0.013, Half divergence angle: 5.6°)	Inlet pressure (bar): 8, C_V: 0.14, COD (ppm): 8000–12,000, pH: 10.5, T (°C): 40, O$_3$ flow rate (g/h): 9.41	**HC:** 12.5% COD reduction (360 min), BI: 0.39 **O$_3$:** 20% COD reduction, BI: 0.32 **HC+ H$_2$O$_2$:** 20% COD reduction (360 min), BI: 0.26 **HC+O$_3$:** 39.7% COD reduction (360 min), BI: 0.34 **Synergetic coefficient: 1.2**	[103]

Cv: Cavitation number; T: temperature; BI: biodegradability index.

8. Summary

Hydrodynamic cavitation has emerged as a versatile processing technology that is gaining significant attention worldwide. Based on the reported outcomes, the following are some of the essential factors that need to be understood during the processing steps of HC:

- The important cavitation factors that affect the emulsification process are attributed to the (a) intensity of turbulence in oil/aqueous phase; (b) viscosity and density of the solution; (c) constriction type, the pressure, and C_v; (d) the number of cavitation passes and concentration of surfactant;
- Enhanced extraction and better pretreatment via HC is dedicated to (a) enhanced diffusion, mass transfer rate, and solvent penetration into cells following the implosion of cavitating bubbles, which generates high pressure as well as temperature in the solution; (b) the generation of active radicals, shock waves, and microjets during the bubble collapse to assist cell disruption and the associated enlargement of pores;
- The efficiency of HC-based treatment depends on several operating parameters, such as solution pH and temperature, HC inlet pressure and type of constriction, the concentration of pollutants, and catalysts;
- Among the various devices reported in the literature, venturies give better degradation efficiency than orifice plates and for the given throat area it is always better to have a device of higher throat perimeter, which can be achieved either by changing the shape of the throat or by making orifice plates of multiple holes of smaller diameter.

9. Conclusions

This review demonstrated that hydrodynamic cavitation could be implemented in several processing steps, which can appropriately harness the effect of bubble implosion. Selecting a proper HC reactor set-up with a suitable constriction type can play a primary role in the overall processing mechanism. Moreover, vital optimum conditions, such as reaction solution temperature, HC inlet pressure, and cavitation number, require attention for the best possible outcomes. The introduction of cavitational phenomena provides reactive radicals, high temperature, and pressure shockwaves, which facilitate biofuel synthesis, the extraction of essential compounds, food processing, assisting the degradation of recalcitrant pollutants, and disinfection of harmful microorganisms. Even though the cavitation-based technology, such as ultrasound, has been widely utilized in the extraction, as well as food processing, HC is emerging as the best alternative method due to its large-scale processing capability. From the reported outcomes, HC has proved to be more effective in wastewater remediation than US- or UV-based advanced oxidation methods. Overall, as a versatile processing technology, HC can be successfully utilized as a greener processing method, while replacing a bunch of traditional techniques. Future investigations should focus on designing a versatile reactor prototype for large-scale applications, with particular attention given to the intensification in bubble generation and their uniform distribution throughout the reaction solution. Also, the development of sunlight-driven reactors should be looked upon for better efficiency.

Author Contributions: All authors of this review have an equal contribution in writing this review. All authors have read and agreed to the published version of the manuscript.

Funding: No funding has been received in writing this review.

Conflicts of Interest: The authors declare no conflict of interest.

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