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Ultrasound Technology Integration into Drinking Water Treatment Train

Raed A. Al-Juboori and Les Bowtell

Abstract

Fresh water is one of the main sources for drinking water production. Due to increasing contamination caused by extreme weather events such as flood and drought as well as urbanization activities, the quality of this source continues to deteriorate. In order to maintain producing high-quality water from heavily contaminated sources, more chemicals are added to water in conventional treatment plants. This practice generates serious health problems such as the formation of disinfection by-products (DBPs) and the increase of coagulants residues (e.g., Al) in the treated water. Combining chemical-free techniques with conventional treatment processes can be a potential solution for such problems. When evaluating various techniques, ultrasound appears to be a sensible choice for improving contaminants removal from surface water. This chapter sheds light on the exacerbating problem of fresh water contamination and succinctly reviews chemical-free techniques' options for water treatment. The focus of this chapter is directed toward providing critical and insightful discussion of fundamentals, mechanisms, and reaction pathways of ultrasound technology for water treatment application. Recommendations for the best location and operating settings of ultrasound application in conventional water treatment train will be provided based on energy saving and minimal downstream impact criteria.

Keywords: ultrasound technology, pulse mode, square wave, dissolved organic carbon, coagulation, filtration and disinfection

1. Common challenges in conventional drinking water treatment systems

Water is an essential element for living systems. It facilitates the transport of nutrients and waste products within the body of living creatures [1]. Surface water is one of the important supplies for drinking water production [2]. Recently, surface water has been increasingly contaminated by microorganisms, organic matter, particles, and solids due to the developing effects of human activities and climate change as is depicted in **Figure 1** [3–5]. This increase in the concentration of surface water contaminants has led to the increase in the cost associated with the treatment of water. The quality of the produced water has also deteriorated as a result of increased contamination. According to the World Health Organization (WHO), 5 million death cases per year worldwide are caused by poor quality drinking water [6]. These problems have made the enhancement of surface water treatment to

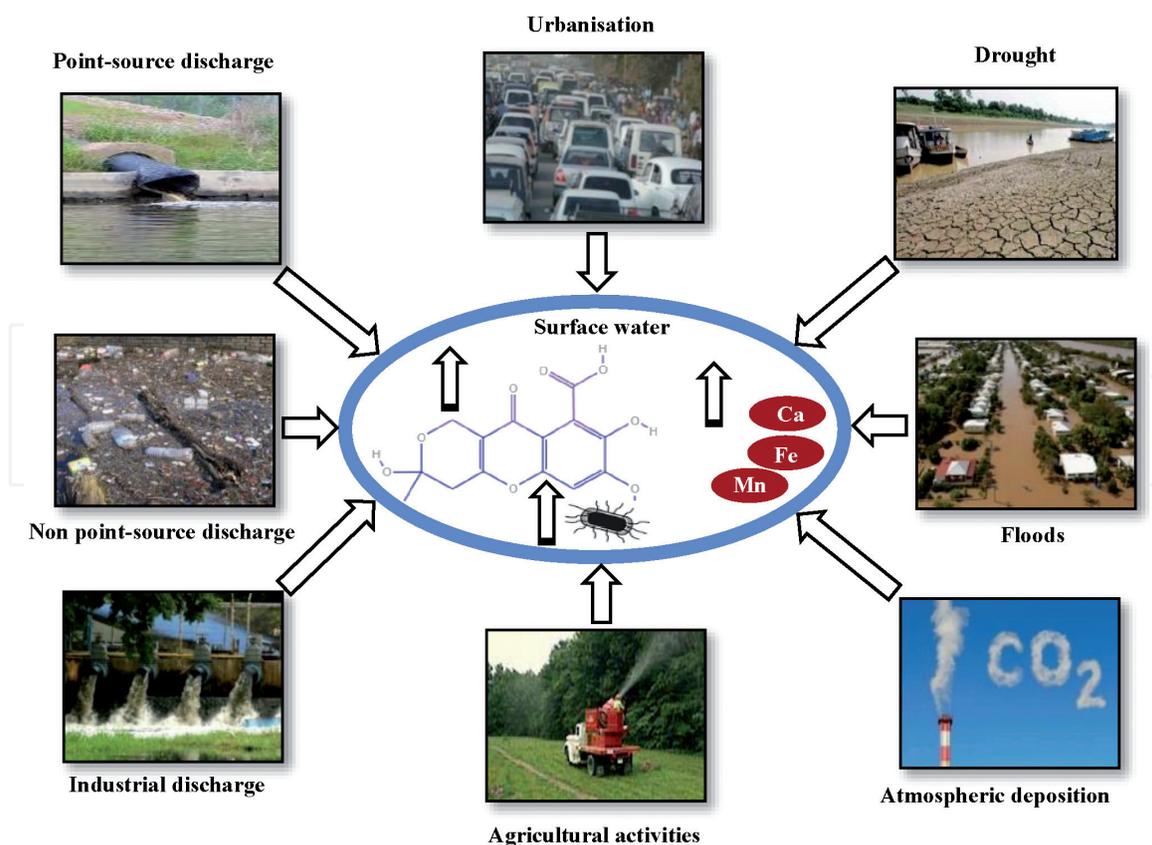


Figure 1.
Sources of surface water contamination.

cope with the increasing levels of contamination, an ultimate goal for the current research activities.

Technically, the performance of surface water treatment systems depends on the efficiency of individual treatment processes in removing contaminants. Conventional surface water treatment systems consist of coagulation/flocculation, filtration, and disinfection [1]. A number of operational and health problems arise in the surface water treatment process as a result of increasing contamination. The most common problems are high level of dangerous residual metal coagulants such as aluminum (Al) [7], fouling of filtration media [8], and the formation of hazardous disinfection by-products (DBPs) [9].

Residual metals can cause operational and health problems. Increasing the Al concentration in water increases turbidity, causes filtration fouling, and interferes with disinfectants [10–12]. In addition to the technical problems, the residual Al in treated water can cause neuropathologic disorders, neurological diseases (e.g., Alzheimer's and presenile dementia), and kidney diseases [10, 13].

Fouling of filtration/adsorption media is another challenge that is commonly encountered in potable water treatment processes. Fouling can occur as a result of the deposition of various foulants, such as solid particles, organic contaminants, inorganic contaminants, and microorganisms, onto various filter surfaces [14]. Fouling of filters results in extra cost and delay on the filtration process as well as reducing the quality of the water produced [15]. The deeply embedded microorganisms in filtration media do not only act as a hidden source of pathogens but also release toxic metabolic products into water treatment systems [16].

The formation of DBPs is a result disinfectants (e.g., chlorine and ozone) reaction with the organic matter [17, 18]. DBPs include a wide spectrum of carcinogenic and mutagenic chemical complexes that pose a threat to both humans and the environment. The two most prevalent classes of DBPs in drinking water are trihalomethanes

(THMs) and haloacetic acids (HAAs) [19]. Total THMs (TTHMs) is the sum of four compounds: chloroform, bromodichloromethane, dibromochloromethane, and bromoform [20]. HAAs include nine compounds which encompass derivatives of HAAs (i.e., mono-, di-, and trihaloacetic acid) and iodine and bromine containing HAAs [19]. The most common HAAs are di- and trihaloacetic acid. Epidemiological and toxicological studies indicated that the human exposure to chlorinated water containing DBPs may lead to bladder cancer [21], deterioration in liver functionalities, kidney and nervous system [22], and congenital diseases [17]. Therefore, a maximum contamination level (MCL) of DBPs has been set for different countries around the world. For instance, the MCL of THMs in Australia is $250 \mu\text{g L}^{-1}$, while the MCL of monochloroacetic acid (MCAA), dichloroacetic acid (DCAA), and trichloroacetic acid (TCAA) are 150, 100, and $100 \mu\text{g L}^{-1}$, respectively [22, 23].

2. Physical methods for drinking water treatment

Research efforts have been directed toward minimizing the challenges encountered in surface water treatment systems. It is obvious that the increasing levels of contamination and the conventional chemicals used for treatment are the main reasons behind these challenges. Hence, the quantities of chemicals added to water should be minimized without compromising the quality of the treated water. To this end, chemical-free (henceforth referred to as physical) treatment methods are recommended to be applied in surface water treatment schemes. It should be mentioned here that this study focuses on organic and microbial contamination; hence, the discussion in the following sections will be confined to aspects pertaining to the removal of such contaminants.

The common physical treatment methods include pulsed-electric field and plasma discharge [24, 25], magnetic field [26], hydrodynamic cavitation [27], ultraviolet (UV) light [28], and ultrasound [29]. The combinations of physical-physical treatments such as UV light and ultrasound and physical-chemical treatments such as ultrasound and chlorine dioxide, ultrasound and ozone, and UV and ozone are also recommended [30].

2.1 Organic contamination

The organic contamination of natural surface water is represented by the existence of natural organic matter (NOM) in water sources. NOM can be categorized based on size into particulate organic carbon (POC) and dissolved organic carbon (DOC). NOM fraction that passes through $0.45 \mu\text{m}$ filter is termed as DOC, while the retained fraction is termed as POC. The latter only forms 10% of NOM and can easily be removed from water [31]. Therefore, attention should be given to improving DOC removal from natural water.

2.1.1 DOC structure

DOC encompasses a vast array of organic materials that varies in their characteristics spatiotemporally [32]. DOC can be classified into groups based on origin and structure. Origin-based classification categorizes DOC into three groups: allochthonous, autochthonous, and anthropogenic [33]. Allochthonous is derived from natural decomposition of soil and plants, while autochthonous DOC is originated from algal and microbial activities. The anthropogenic DOC in surface water is emanated from human activities and wastewater treatment processes [33]. Potable water sources contain mainly allochthonous and autochthonous carbon [34]. The

concentration of autochthonous DOC in surface water depends strongly on the hydraulic residence time of water in reservoirs and this would naturally reduce its contribution to overall organic contamination. Hence, improving allochthonous DOC removal would be of more importance to drinking water treatment practices.

The structural classification mainly divides DOC into hydrophobic and hydrophilic fractions [35]. The proportion of these fractions in natural water catchments depends on the carbon source and other factors such as microbial activities and natural photo-degradation. The hydrophobic fraction is comprised mainly of humic and fulvic acids, phenolic DOC, and double bond structures [36]. The hydrophilic fraction mainly contains aliphatic and nitrogenous compounds [35]. DOC structure is important from water treatment perspective as these fractions are associated with certain health and operational problems [37]. For instance, hydrophobic DOC is known to have a tendency to react with chlorine forming DBPs [38].

2.1.2 DOC removal mechanisms

The main DOC removal mechanisms of physical treatments are (i) chemical reactions (e.g., radicals attack), (ii) physical effects (e.g., shear forces, pyrolysis), and (iii) alteration of physical properties (absorptivity). A wide range of radicals are produced when exposing water to physical treatments such UV and ultrasound. The most important radical species is the hydroxyl ($\cdot\text{OH}$) as it possesses a high oxidation potential (2.8 V) that exceeds the oxidation potentials of common oxidants such as atomic oxygen (2.42 V), ozone (2.07 V), and hydrogen peroxide (1.78 V) [39]. The $\cdot\text{OH}$ pathway reactions with NOM include addition to double bonds and hydrogen and electron abstraction [35]. Chemical mechanisms are prominent in electrical and UV techniques, while the combination of both chemical and physical mechanisms is generated with techniques such as ultrasound and hydrodynamic cavitation [40]. Physical treatments that utilize magnetic fields can alter physical properties of DOC, making it more susceptible to removal via adsorption [6, 26]. It is worth mentioning that physical methods that produce $\cdot\text{OH}$ are also capable of altering the nature of remnant DOC [41].

2.1.3 DOC removal with physical methods

Generally, DOC removal levels are low with the physical treatments as stand-alone technologies; however, combining these methods with chemicals addition can significantly boost DOC removal [35]. Chemical addition to some treatment methods such as UV and electrical methods can be problematic. For instance, the addition of TiO_2 in photo-catalysis (UV/semi-conductors) requires an additional treatment to remove TiO_2 particles from the treated water, and this in turn introduces extra cost [42]. The addition of electrolytes such as NaCl [35], or KCl [43] in electrochemical oxidation can also cause some technical problems such as the conformational change of DOC [44] resulting in a compact fouling layer. Electrodes and UV lamps are also prone to fouling problems that require frequent maintenance [45]. Furthermore, the use of UV method, particularly vacuum UV (VUV), was found to produce undesired nitrite by-products [35]. Similarly, magnetic field technique can potentially cause some health problems. It was reported that the use of magnetically treated water negatively affects the functionality of rats' kidneys suggesting that magnetic treatment can cause unstable changes to bio-mechanisms of tissue fluid [46]. Generally, electrical, magnetic, and UV treatments require mixing to ensure uniform effective treatments which adds to energy requirements of these techniques. By way of contrast, mixing is not required for dynamic treatments such as ultrasound and hydrodynamic cavitation. These treatments were also found

to have benign environmental effects [47]. However, hydrodynamic cavitation has some disadvantages such as the unclear effect of operating parameters on cavitation events [48], the requirement of long treatment time to achieve perceptible change, and mechanical erosion of equipment [47]. The main disadvantage of ultrasound is high operational energy demand [49], nevertheless the installation and maintenance cost is low due to its simple configuration [50]. Recent studies have reported that ultrasound is more energy efficient compared to hydrodynamic cavitation and UV in removing organic materials [25].

2.2 Microbial contamination

Various species of microbes are present in surface water. However, microbial contamination of water is normally evaluated through indicators such as total coliform and *E. coli* [51]. The mechanisms of microbial removal/inactivation using physical treatment methods are similar to those of NOM removal. The produced highly oxidative agents attach the structure of microbes weakening their resistance to the surrounding environmental conditions. Similar microbial structural damage can be induced by the strong mechanical effects such as powerful turbulences and shockwaves. Generally, UV and electrical disinfection techniques rely on chemical effects; with ultrasound and hydrodynamic cavitation, the mechanical effects have a more prominent role as opposed to thermal and chemical effects [52].

As far as the performance is concerned, UV and electrical techniques have the disadvantages of producing mutagenic activities and low performance with turbid water [14, 53]. Hydrodynamic cavitation has some shortcomings as mentioned in Section 2.1.3. In contrast, ultrasound technology has advantages of being environmentally friendly and easy to implement and control, which outweighs the disadvantage of high energy demand. Even the high energy demand reputation for ultrasound technology may be attributed to the inefficient utilization of energy in this technology which will be discussed further in the coming sections.

Given the potential of ultrasound technology in solving the emerging problems in drinking water treatment process, this chapter will provide critical review on this matter.

3. Ultrasound technology

3.1 Fundamentals of ultrasound

Ultrasound is a longitudinal wave with frequency ranges between 16 kHz and 500 MHz [54]. The propagation of ultrasound waves through water produces alternating cycles of positive and negative pressure. When the magnitude of the ultrasonic pressure exceeds the tensile strength of the liquid, cavitation bubbles are created. The formed cavitation bubbles and existing gas bubbles in the liquid grow to a size larger than their original size during the negative cycle of the ultrasonic pressure. Some bubbles grow to a very large size due to gas transfer across bubble skin (rectified diffusion) or coalescence with other bubbles, and eventually float to water surface. Other bubbles collapse during the positive cycle of the ultrasonic wave. In terms of collapse intensity, there are two kinds of bubbles; bubbles with gentle collapse “stable bubbles” and bubbles with severe collapse “transit bubbles” [55]. There are two sources for bubbles generated in ultrasonically excited water: dissolved gas and gas entrapped in crevices of solid surfaces. The formation of bubbles from dissolved gas is normally termed as homogeneous cavitation, while bubbles formation on liquid-solid interface is termed as heterogeneous cavitation [56].

The physics and chemistry of transit bubbles are of interest from water treatment perspective owing to the powerful effects produced from such bubbles collapse. These effects are represented by the generation of localized areas of high temperature and pressure of around 5000 K and 500 atm, respectively, usually referred to as hot spots [40]. There is a variation in the temperature profile within the localized areas of hot spots which determines the nature of reactions occurring in each area. The three recognized zones of the hot spots are [40, 57]:

- A. **Thermolytic center** represents the center of the cavitation bubble. During bubble collapse, the temperature and the pressure of this zone reach approximately 5000 K and 500 atm, respectively. The material phase in this region is gaseous, so it can be inferred that the high temperatures in this region can lead to the thermolysis of the volatile DOC and water vapor exist in the region [58]. The thermolysis of water vapor produces free radicals that can further decompose volatile DOC.
- B. **Interfacial zone** is present between bubble skin and the bulk solution. The thickness of this region is around 200 nm, and the life time of this region is about 2 μ s [57]. The temperature in this region reaches to approximately 2000 K at the final collapse of the bubble [59]. The material phase in this region is a supercritical fluid. The high temperature in the interfacial zone facilitates the thermolysis and the oxidation of nonvolatile DOC.
- C. **Bulk solution region:** the pressure in this region is equal to the ambient pressure; whereas, the temperature is variable depending on ultrasound operating parameters. The hydroxyl radicals recombine in the bulk solution region producing hydrogen peroxide, which in turn can oxidize nonvolatile DOC.

Bubble's oscillation and collapse generate acoustic streaming, microstreaming, microjetting, turbulence, shock wave, and shear stress [60]. Acoustic streaming is defined as the convective liquid motion due to the passage of ultrasound waves. Microstreaming is the liquid motion in the adjacent area to oscillating bubbles. Microjetting is the resulting liquid motion from bubble symmetrical collapse close to the solid/liquid interface [61]. The physical and chemical effects of ultrasound can be harnessed for organic and microbial contamination removal.

3.2 Effects of acoustic cavitation events on water contaminants

Figure 2 illustrates the physical and chemical effects of ultrasound on water contaminants. The physical effects such as the powerful turbulences and shock waves can disintegrate organic and microbial structures, as reported by several studies [49, 60].

Chemical effects of ultrasound are evident through the liberation of highly reactive species that have the capacity to cleave chemical bonds. The reactive species are short lived intermediates [62]; therefore, their effect is expected to occur only during the short time of the bubble's collapse. As explained earlier, volatile compounds are likely to decompose in the thermolytic center due to the effects of free radicals.

The nonvolatile compounds in water are divided into two groups: hydrophobic and hydrophilic compounds. The repulsive nature of hydrophobic compounds to water forces these compounds to accumulate in the area adjacent to collapsing bubbles, which in turn facilitates the ultrasonic-induced chemical decomposition of these compounds by free radicals, as demonstrated in **Figure 2**. The case is different for nonvolatile hydrophilic compounds, as the concentration of such compounds in the sheath around the bubble is similar to that in the bulk solution region. So the hydrophilic compounds are either chemically disintegrated by free radicals and their

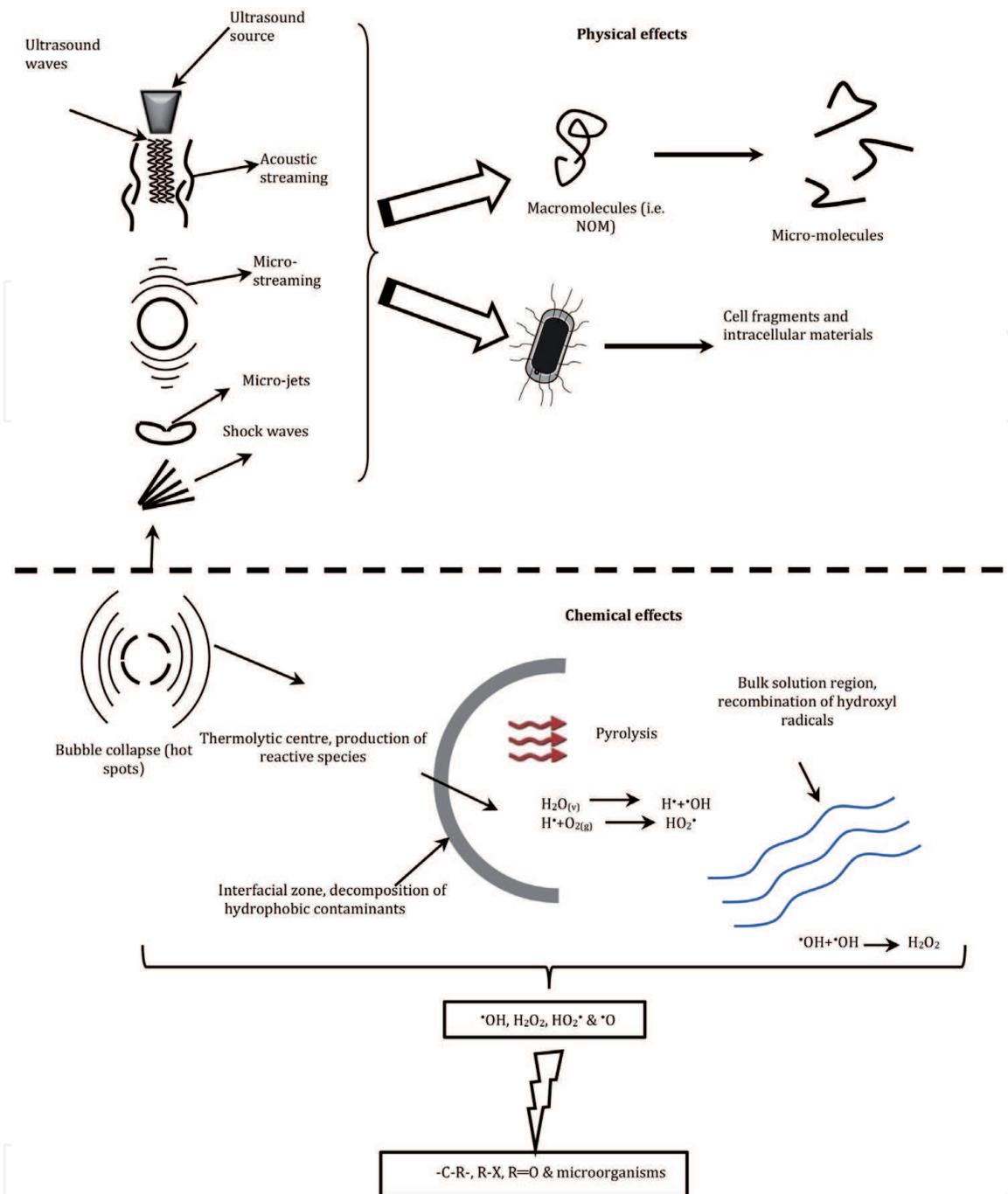


Figure 2. Mechanisms of acoustic cavitation in degrading water pollutants.

recombination products or mechanically destructed via the mechanical shear and shock waves resulting from bubble oscillations and collapse [63]. The shear stresses' and shock waves' degradation of organic materials is attributed to the slight phase difference, especially for humic polymeric structures. Many researchers have reported the capacity of shear stresses and shockwaves on breaking the chain structure of polymeric organic materials or opening the ring structure of cyclic organic materials [57]. Additionally, the extreme conditions in the collapsing bubble's center and the surrounding areas can lead to the formation of acids [64], which can reduce the solubility of humic acid and consequently increases its degradation by the physical effects.

Although inorganic contaminants are outside the scope of this study, it is worth mentioning that microstreaming and generated oxidative species instigated by bubble collapse are the main ultrasonic removal mechanisms for these contaminants [65].

3.3 Methods of producing ultrasound waves

Ultrasound waves are commonly generated by converting electrical power into vibration using transducers. There are two types of transducers: piezoelectric and magnetostrictive [66]. A graphical representation of these transducers is shown in **Figure 3**. For piezoelectric transducers, the vibration is created via exciting the piezoelectric crystal with electrical current, as demonstrated in **Figure 3a**. In the case of magnetostrictive transducers, the electrical current is passed through coils inducing a magnetic field that causes contraction and expansion of the ferromagnetic core (Terfenol-D or Nickel in most cases), as shown in **Figure 3b**. Comprehensive comparison between the characteristics of magnetostrictive and piezoelectric transducers is provided in [67]. Although the performance of magnetostrictive transducers outstrips that of piezoelectric transducers [68, 69], there is limited number of studies concerning the use of these transducers for water treatment applications.

3.4 Modes of operation

Ultrasound irradiation can be applied in two modes: continuous and pulsed. Continuous mode is more commonly used for water treatment application compared to the pulsed mode. In pulsed mode, the operation is interrupted for a preset amount of time. The period during which ultrasound operates is known as pulse; whereas, the interruption time is normally termed as interval. The pulse and interval are denoted, respectively, as *On* and *Off* periods. The *On:Off* ratio is commonly denoted as *R*. Operating ultrasound in a pulsed mode is more energy-efficient due

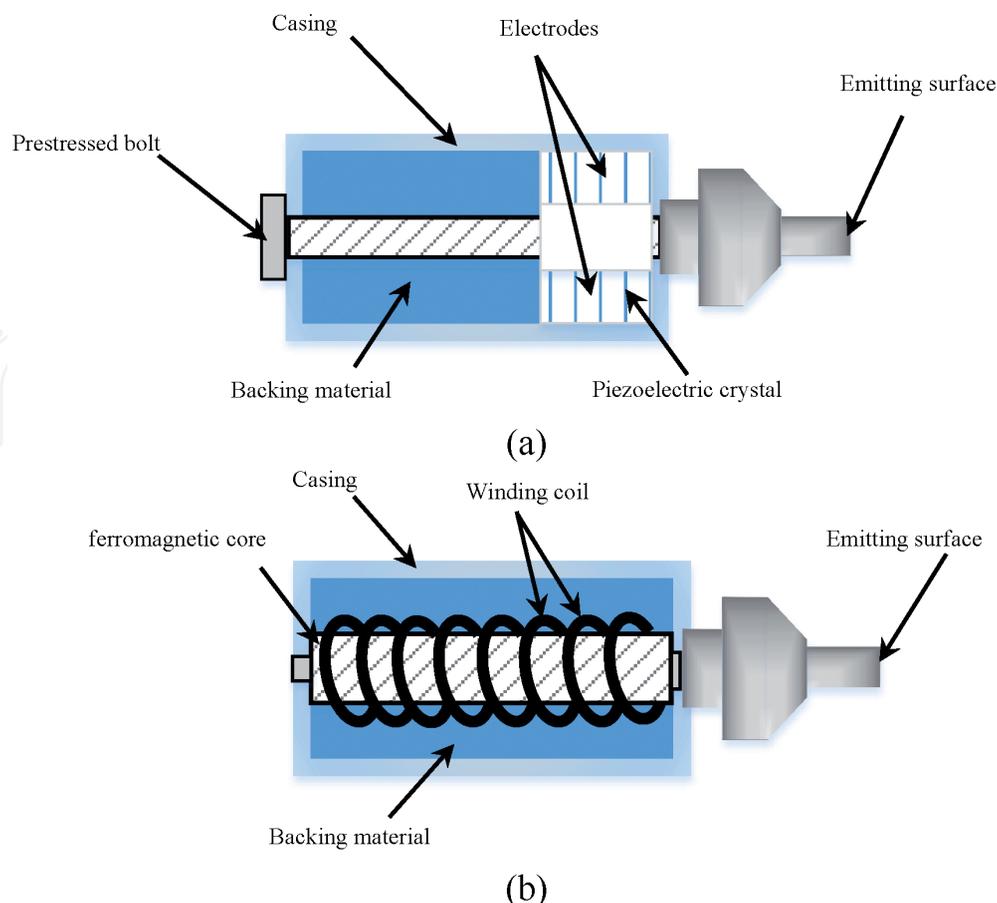


Figure 3. Common ultrasonic wave generation techniques: (a) piezoelectric and (b) magnetostrictive.

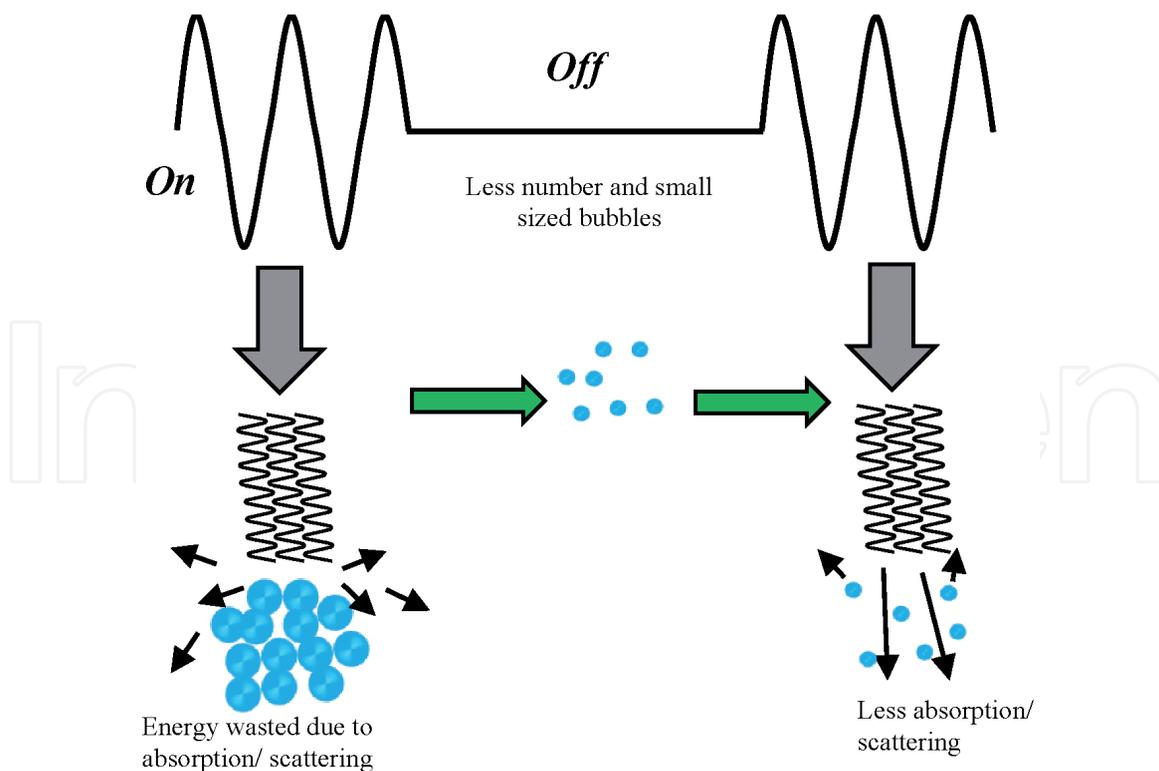


Figure 4.
Illustration of pulsed mode alleviation of shielding effects.

to minimizing bubble's cloud size that occurs near the irradiating surface especially at high-power levels (reduction of shielding effects) [57]. During the *Off* period, the ineffective cloud bubbles dissolve and/or float to the surface leaving less number of ineffective bubbles close to the irradiating surface, which means less energy is absorbed/scattered by bubbles [70], as illustrated in **Figure 4**. Other positive aspects of applying pulsed mode ultrasound include improvement of pollutants transport to reaction sites of collapsing bubbles, spatial enlargement of the active zone, and utilization of acoustic residual energy during the *Off* period. Operating ultrasound in pulsed mode also reduces temperature rise that can be undesirable for some water treatment applications such as filtration [14].

Operating ultrasound in pulsed mode does not always result in improved performance [71]; it depends on applying a suitable power level for the chosen *R* ratio. Hence, optimizing pulse ratios and power levels are of utmost importance for pulsed ultrasound applications. Using pulsed ultrasound for water contaminants removal was investigated by a limited number of studies, such as the studies conducted by [72, 73]. These studies dealt only with synthetic water samples. Recent studies proved the capability of pulsed ultrasound in removing natural water contaminants [74].

3.5 Parameters affecting ultrasound effectiveness

Like other treatment technologies, the performance of ultrasound is influenced by several factors. These factors can be broken down into three groups: system operating conditions, medium characteristics, and design-related aspects. The operating parameters of ultrasonic equipment include power, frequency, treatment time, mode of operation, and shape of the exciting waves (i.e., sine, triangle, etc.). It is known that increasing the power results in more intense ultrasonic effects; however, power impact normally follows a logarithmic growth trend, where increasing beyond a certain limit can only result in little improvement. Frequency has a direct

relationship with cavitation threshold; therefore, the higher the frequency, the more the power required to generate cavitation bubbles [75]. As discussed in the previous section, pulsed mode is more energy-efficient than the continuous mode. Among the common exciting waves' shapes, square wave has the highest ultrasonic effects [67].

Medium characteristics such as viscosity, pressure, temperature, and contents of solid and gas impurities can affect the intensity of ultrasound effects. Viscosity has a negative effect on the generation and collapse of cavitating bubbles. It is difficult for ultrasonic waves to propagate through a viscous medium due to high cohesion forces; hence, less effective acoustic events would be achieved [76]. In the case of typical surface water treatment system, change in water viscosity is not expected to occur, and hence the effect of this factor can be ignored. The effect of the ambient pressure on ultrasound comes into play only when dealing with closed system treatment chambers. Increasing the ambient pressure has two conflicting effects: decreases the vapor content in the collapsing bubble leading to more effective bubble collapse [54] and at the same time negatively affects bubble growth leading to less violent collapse [77]. The ambient temperature impacts ultrasound performance in a similar fashion. Increasing the temperature facilitates bubbles formation due to reduction in medium viscosity; however, the vapor content in the formed bubbles would be high leading to a less violent collapse (cushioning effects) [77]. It should be mentioned that increasing the ambient temperature can accelerate both microbial disruption and chemical reactions under the effect of ultrasound [54, 77]. This means that the net temperature effect on ultrasound performance is positive.

The impact of solid particles and dissolved gas bubbles depends on their nature and the treatment purpose. Bubbles formed from gases with high specific heat ratio produce better cavitation effects (higher temperature and larger number of radicals) compared to those generated from gases with low specific heat ratio [78]. The presence of solid particles in water can be beneficial if the treatment is targeting microbes' removal [79, 80], or adverse if the treatment goal is DOC removal [81]. In the case of surface water treatment, the dissolved gas would mostly be air resulting in relatively high acoustic effects compared to other gases such as O₂ and Ar [82]. The presence of solids in surface water is inevitable, and they would be a mixture of soil aggregates that release DOC upon ultrasound exposure [81] and solid particles that promote heterogeneous cavitation [80].

The aspects of ultrasonic reactor design such as reactor shape and liquid height play crucial roles in the homogeneity of acoustic energy distribution and the uniformity of treatment across the treated volume. Generally, reactors with curvatures (e.g., conical or cylindrical) are more effective in utilizing ultrasound power compared to the standard rectangular-shaped reactors [83, 84]. This is attributed to the reflection of the waves back from the curved walls to the water in different directions resulting in more acoustic events. However, reactors with flat surfaces are easier to design and modify to accommodate monitoring and measurements equipment [57]. An example of such a design is the hexagonal reactor proposed by Gogate et al. [85], where waves can still be reflected from the walls. The liquid height has a negative effect on ultrasound performance; the further away the contaminants are from ultrasonic source, the less effective the treatment is [57]. Interestingly though, in a study conducted by Asakura et al. [86] on the effect of liquid height on ultrasound chemical activity at different frequencies showed that at largest height investigated (500 mm), low frequency ultrasound resulted in the highest chemical throughput compared to other tested frequencies (>100 kHz). In the same manner, Sharma and Sanghi [87] reported that low frequency results in better distribution of acoustic energy in large-scale volumes. This suggests that low frequency ultrasound operation has the potential to be successfully scaled up to industrial levels.

3.6 Ultrasound scalability in surface water treatment

The scalability of ultrasound technology for drinking water treatment purposes requires multi-disciplinary expertise such as chemistry, electrical engineering, chemical engineering, material sciences, etc. One essential step toward scalability is applying an accurate energy characterization technique. The use of an inappropriate characterization method would produce discouraging energy figures that would be disincentive for industries interested in adopting ultrasound technology.

There are many techniques for determining the capacity of ultrasound equipment in converting electrical power to useful acoustic energy. Among all the reported energy characterization techniques, calorimetric technique is the most commonly used owing to its simplicity and cost-effectiveness [88]. However, this technique must be carefully applied. The use of a single location for temperature measurements as being representative for the whole irradiated volume is not appropriate, especially for low power levels where standing wave effects are evident [89]. The other aspect that needs to be carefully considered is the heat loss via convection during the time of temperature recording. Convective heat loss would be more noticeable in the cases of high-power application and pulsed operation. At high ultrasonic power, the temperature rise is rapid which would accelerate thermal energy dissipation through the walls of the containing vessel to the atmosphere. In the case of pulsed ultrasound, long irradiation time is required to obtain tangible temperature rise and this would allow enough time for the generated heat to escape to the atmosphere. This explains why some studies have reported efficiency as low as 30% for ultrasonic horn [90], while others reported efficiency as high as 60–70% [91] for the same reactor type, as the latter used a sophisticated adiabatic reaction vessel that prevents convective heat loss.

Many scale-up attempts of ultrasonic reactors were reported in the literature [92]. The prominent approaches were: multistage reactors [49], flow-cells [93], sonitube [89], super-positioning multiple transducers of similar or different frequencies [57], and the use of reflectors [94, 95]. The approach of combined multi-transducers and reflectors seems to be a promising strategy for ultrasonic reactor scale-up as the interaction of waves emitted from transducers and the reflected waves from reflectors would enlarge the active zone in the reactor. However, it is worth mentioning that most of these scale-up attempts utilized the commercially available piezoelectric transducers that operate largely on sine wave excitation. Recent studies have shown that some waveforms other than the sine wave can result in better excitation of transducers [96]. Thus, exploring the use of other transducer types and waveforms in large-scale applications is imperative to provide broader and may be more efficient options to industry.

3.7 Ultrasound application in water treatment processes

3.7.1 Coagulation/flocculation

The common use of ultrasound in coagulation process is as a pre-treatment for the process to improve blue-green algae removal [97]. The presence of blue-green algae in the water treatment system has been associated with many problems such as clogging membrane pores, undesirable taste and odor, production of DBPs, and the release of toxic compounds such as Microcystin [98]. Ultrasonic mechanism for algae removal is ascribed to the destruction of gas vacuoles that are responsible of algae buoyancy [97]. There is also a recent study that has utilized ultrasound as a mean of mixing for algae removal using chitosan [99]. Removing algae requires applying low frequency, moderate input power, and short treatment time.

The application of low power ultrasound for a short treatment time in algae removal applications can solve the seasonal problem of algal bloom, but it does not tackle the problems of other forms of contamination that occur all year around. For better implementation of ultrasound in water treatment, the use of moderate to high ultrasonic power and long treatment should be applied for such applications. There is a very limited work conducted on the use of high-power ultrasound in combination with coagulation such as the work performed by Ziylan and Ince [100]. However, this work only focused on DOC removal levels, while DOC structural change and downstream effects of the treatment were not investigated. These factors were explored in [74], and it was found that ultrasound is not only capable of removing contaminants, but it also alters the structure of remnant contaminants making them more amenable to downstream treatment processes. It was also observed that ultrasound application eliminated scum formation and resulted in more compact coagulation/flocculation sludge.

3.7.2 Filtration

Ultrasound technology has been harnessed by many investigations for alleviating fouling problems in membrane filtration. Ultrasound-assisted membrane technology can be applied in two ways: cleaning or pre-treatment techniques. Ultrasonic cleaning of membrane filtration can be performed directly or indirectly. In direct ultrasonic-membrane cleaning, there is no barrier that isolates the membrane from ultrasound irradiation [57]. In an indirect ultrasonic-membrane cleaning, the membrane is isolated from ultrasonic irradiation by the membrane cell body. Most of the reports regarding ultrasound-cleaning membranes dealt with flat sheet membranes; however, in a few cases, ultrasound was also used for cleaning hollow fiber membrane modules [101] and capillary membrane fibers [102].

Although ultrasonic cleaning has been recognized by many studies as an effective alternative to chemical cleaning, there are still some shortcomings that limit its application in membrane fouling control such as dependence of cleaning effectiveness on the distance between the effective cavitation region and membrane and the detrimental effect on membrane construction materials, as shown in **Figure 5**. Deteriorating the

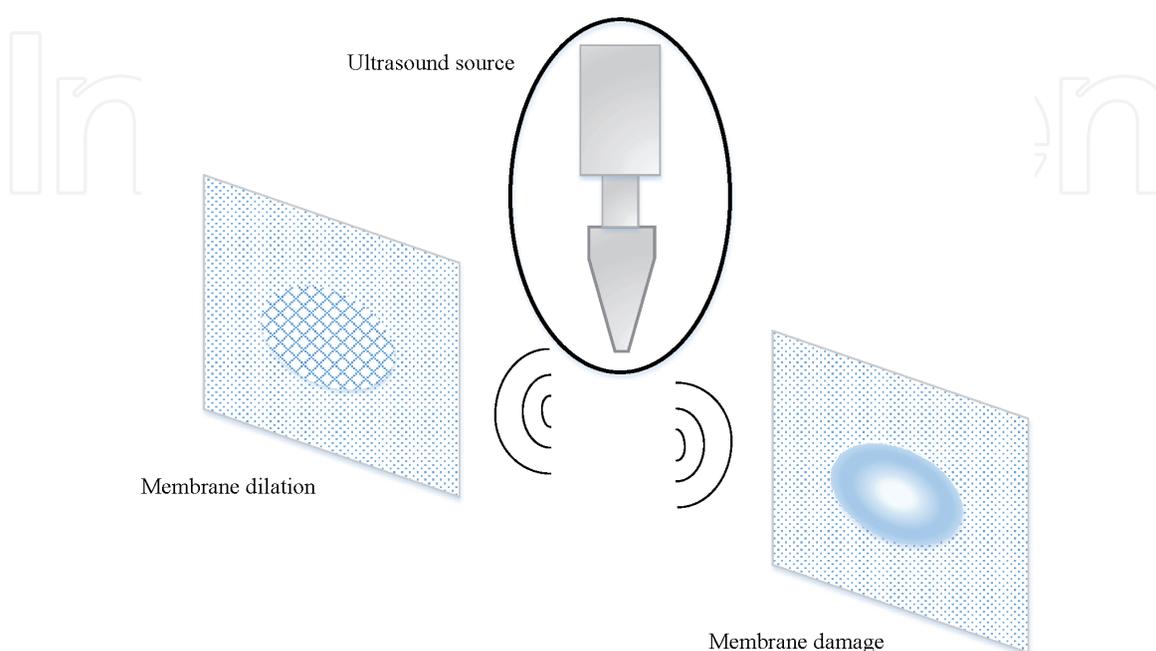


Figure 5. Illustration of negative effects of direct high-power ultrasound on membrane structure.

structure of the membrane filter could potentially lead to a failure in filtration. Thus, the direct interaction between ultrasonic irradiation and membrane should be avoided, especially for high-power applications (up to and beyond cavitation).

As a pre-filtration process, it was found that ultrasound is capable of reducing bio-fouling formation in membrane systems [103]. Ultrasound can also remove other contaminants, as indicated in **Figure 2**. In spite of the advantages of ultrasound as a filtration pre-treatment, there are some concerns related to the disintegration of the contaminants into smaller sizes, which may then lead to a pore-plugging type of fouling [104]. For this reason, distancing ultrasound from the filtration process is recommended.

3.7.3 Disinfection

Ultrasound is recognized as the most effective disinfection technique for all forms of microbial contamination even for recalcitrant microbes and spores [47, 49, 77, 105–107]. As explained in Section 3.2, the powerful biocidal effects of ultrasound are attributed to the strong chemical and mechanical effects produced from cavitation bubble's collapse. Disinfection is typically applied after filtration at the end of the surface water treatment process. The purpose of disinfection is to disinfect water onsite and prevent microbial growth in the water while moving within the distribution network. However, as ultrasound has no residual effect, it would be more beneficial to apply ultrasound in the earlier stages of surface water treatment.

4. Conclusions and recommendations

The recent challenges in drinking water treatment industry emanating from the ever-increasing contamination sources and the application of traditional chemical treatment methods have been highlighted in this chapter. Integrating physical techniques into the conventional drinking water treatment scheme has been proposed as a potential solution for these challenges. Among the common physical techniques, ultrasound technology appears to be the most promising option. Ultrasound can produce powerful effects associated with the generation and collapse of unstable bubbles. These effects are capable of destructing microbes and mineralize organic contaminants through the production of highly oxidant species and strong mechanical effects. Appropriate utilization of ultrasound effects can only be achieved through understanding the relationship between ultrasonic parameters and the properties of the water being treated. The effect of some ultrasonic parameters such as power and frequency are extensively investigated for different treatment goals; however, this chapter attempts to draw the attention to other equally important parameters such as techniques of ultrasonic wave generation, mode of operation, and the shape of the generated waves. It appears that the best ultrasonic settings for water treatment application are moderate to high power for long treatment time, low frequency, pulsed mode, and square wave generated using magnetostrictive transducer. After critical evaluation of the possible combination scenarios of ultrasound with main drinking water treatment processes, it was concluded that applying ultrasound prior to coagulation is the most beneficial option as other combinations may create adverse downstream effects. Hence, further in-depth investigation for the suggested combination is recommended for future research work.

Conflict of interest

The authors declare no conflict of interest.

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