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Ultrasound Irradiation: Fundamental Theory, Electromagnetic Spectrum, Important Properties, and Physical Principles

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1.1 Introduction

US, also referred to as ultrasonic treatment or sonication, employs high frequency sound waves to agitate particles in a liquid or solid medium [1]. This process relies on the phenomenon of cavitation, which happens when high-intensity sound waves create small bubbles in a liquid. These bubbles rapidly expand and collapse, producing pressure and temperature gradients that can break down particles and disrupt chemical bonds. This is known as acoustic cavitation, and it can be utilized for various purposes, including emulsification, dispersion, mixing, and extraction. Additionally, US can increase the surface area of reactants and enhance chemical reactions by promoting mass transfer between phases. It can also induce the formation of free radicals, which can react with target compounds and break them down. US is widely used in a range of fields, such as wastewater treatment, food processing, pharmaceuticals, and materials science [2–4]. The effectiveness of US depends on several factors, such as the frequency and intensity of the sound waves, the duration of exposure, and the characteristics of the medium being treated. Cavitation can be generated either by passing ultrasonic energy in the liquid medium or by utilizing alterations in the velocity/pressure in hydraulic systems. The intensity of cavitation, and hence the net chemical/physical effects, relies heavily on the operating and design parameters, including reaction temperature, hydrostatic pressure, irradiation frequency, acoustic power, and ultrasonic intensity. To increase the extent or rate of reaction, cavitation can be combined with one or more irradiations or some additives can be utilized, which can be solids or gases and can sometimes have catalytic effects. The free radicals generated during the oxidation process consist of hydroxyl ($^{\bullet}OH$), hydrogen ($^{\bullet}H$), and hydroperoxyl ($HO_2^{\bullet}$) radicals. Overall, the theory behind US is based on the principles of acoustic cavitation, which can be harnessed to achieve a variety of physical, chemical, and biological effects.

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US refers to the application of high-frequency sound waves to a target material or medium. Here are some properties of US:

Frequency: Ultrasound waves have frequencies above the upper limit of human hearing, typically between 20 kHz and several MHz (megahertz). The frequency determines the energy and penetration depth of the ultrasound waves.

Wavelength: The wavelength of ultrasound waves is inversely proportional to the frequency. Higher frequencies result in shorter wavelengths. This property allows ultrasound waves to interact with small-scale structures and particles.

Intensity: Ultrasound intensity refers to the amount of energy carried by the sound waves per unit area. It determines the strength of the ultrasound waves and their effect on the target material. Ultrasound intensity is typically measured in units of watts per square centimeter (W/cm^2).

Propagation: Ultrasound waves propagate through materials as longitudinal waves, causing the particles of the medium to vibrate in the direction of wave propagation. This enables the transmission of energy and information through the medium.

Absorption: Ultrasound waves can be absorbed by materials they pass through. The extent of absorption depends on the properties of the material, such as its density, viscosity, and composition. Absorption leads to the conversion of ultrasound energy into heat, which can be utilized in various applications.

Reflection and refraction: When ultrasound waves encounter an interface between two different media, such as air and a solid object, some of the waves are reflected back and some are transmitted into the new medium. The angles of reflection and refraction obey the laws of physics similar to those governing light waves.

Cavitation: US can induce a phenomenon known as cavitation, where the rapid changes in pressure cause the formation and implosion of tiny bubbles in a liquid medium. Cavitation can generate localized high temperatures and pressures, which can be utilized in processes like sonochemistry and ultrasonic cleaning.

Noninvasiveness: Ultrasound waves can be transmitted through the body noninvasively, making them useful in medical imaging techniques like ultrasound scans and sonograms. They provide real-time visualization of internal organs, tissues, and structures without the need for surgery or ionizing radiation.

Doppler effect: The Doppler effect occurs when there is relative motion between the source of ultrasound waves and the target. This effect causes a shift in the frequency of the reflected waves, enabling the measurement of blood flow, velocity, and direction in medical applications like Doppler ultrasound [5, 6].

Safety: US is generally considered safe for medical and industrial applications, as it does not involve ionizing radiation like X-rays or gamma rays. However, high-intensity ultrasound can cause thermal effects, and prolonged exposure to certain intensities may have biological effects. Safety guidelines and standards are in place to ensure the safe use of ultrasound in different applications.

1.2 Cavitation History

The phenomenon of cavitation was first observed by Thornycroft and Barnaby in 1895 when the propeller of their submarine became pitted and eroded over a short operating period. This was due to collapsing bubbles caused by hydrodynamic cavitation, which generated intense pressure and temperature gradients in the surrounding area [7]. In 1917, Rayleigh published the first mathematical model describing a cavitation event in an incompressible fluid [8]. It was not until 1927, when Loomis reported the first chemical and biological effects of ultrasound, that researchers realized the potential of cavitation as a useful tool in chemical reaction processes [9]. One of the earliest applications of ultrasound-induced cavitation was the degradation of a biological polymer [10]. Since then, the use of acoustic cavitation has become increasingly popular, particularly as a novel alternative to traditional methods for polymer production, enhancing chemical reactions, emulsifying oils, and degrading chemical or biological pollutants [11]. The advantage of utilizing acoustic cavitation for these applications is that it allows for much milder operating conditions compared to conventional techniques, and many reactions that may require toxic reagents or solvents are not necessary.

1.2.1 Basics of Cavitation

Ultrasound is a type of sound wave with a frequency above 20 kHz, and when it propagates through a liquid medium, it can create conditions for cavitation. Ultrasound has been extensively used as an intensifying approach in various fields, including chemical synthesis, electrochemistry, food technology, environmental engineering, materials, and nanomaterial science, biomedical engineering, biotechnology, sonocrystallization, and atomization [2, 12–21]. The use of ultrasound can lead to greener intensified processing with significant economic savings [22, 23]. Ultrasound-induced cavitation, also known as acoustic cavitation, is mainly due to the alternate compression and rarefaction cycles that drive the various stages of cavity inception, growth, and final collapse, as shown in Figure 1.1 [12].

When cavities collapse, a significant amount of energy is released, leading to the formation of acoustic streaming associated with turbulence resulting from the continuous generation and collapse of cavities in the system. Moreover, chemical effects, such as the occurrence of local hotspots in the interfacial region between the bubble and adjacent liquid, can generate free radicals [24]. The primary reactions that occur during sonication can be considered the initiator of a series of radical reactions depending on the species:

$$\mathrm{H_2O} \leftrightarrow {}^{\bullet}\mathrm{OH} + {}^{\bullet}\mathrm{H} \tag{1.1}$$

$$\mathrm{H}^{\bullet} + \mathrm{H}^{\bullet} \leftrightarrow \mathrm{H_2} \tag{1.2}$$

$${}^{\bullet}\mathrm{OH} + {}^{\bullet}\mathrm{OH} \leftrightarrow \mathrm{H_2O_2} \tag{1.3}$$

$$\mathrm{H}^{\bullet} + \mathrm{O_2} \leftrightarrow \mathrm{HO_2}^{\bullet} \tag{1.4}$$

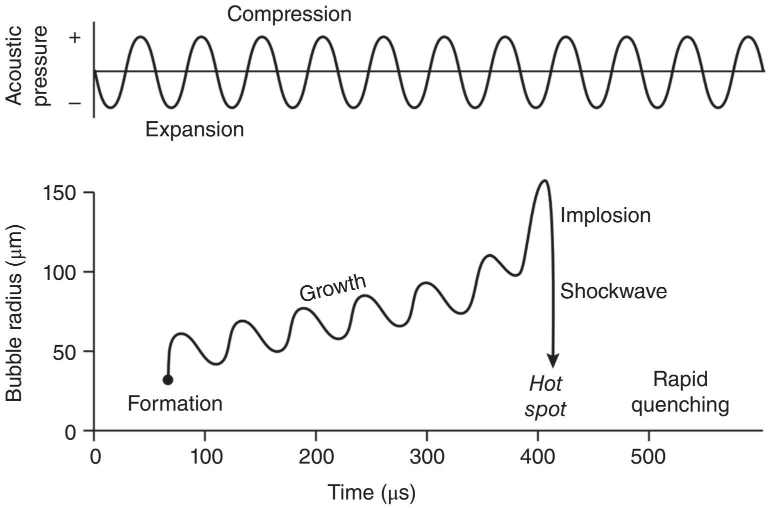

Figure 1.1 Schematic representation of the mechanism of generation of acoustic cavitation. Source: Reproduced from Gogate et al. [12]/John Wiley & Sons.

$$H^{\bullet} + HO_2^{\bullet} \leftrightarrow H_2O_2 \qquad (1.5)$$

$$HO_2^{\bullet} + HO_2^{\bullet} \leftrightarrow H_2O_2 + O_2 \qquad (1.6)$$

When ultrasound is applied to water, it causes the generation of $^{\bullet}OH$ and $H^{\bullet}$ radicals, which subsequently leads to the production of hydrogen peroxide (H_2O_2). Both of these agents are strong oxidizing agents. As the cavitation bubble collapses, it generates tremendous local pressure gradients, temperature, and microjets in the liquid at the collapse point [25]. The release of the accumulated energy during bubble collapse in the form of shock waves and hot spots can significantly enhance the reaction rate [26]. In large-scale sonochemical reactors, the two most important features of cavity dynamics are the maximum size reached before the violent collapse and the intensity of the collapse. Maximizing both of these effects in large-scale designs is necessary to achieve the desired processing efficacy.

The chemical changes associated with cavitation induced by the passage of sound waves are referred to as sonochemistry [1]. Ultrasound's chemical effects do not arise from direct interaction with molecular species but rather from acoustic cavitation, which involves the formation, growth, and implosive collapse of bubbles in a liquid, resulting in very high energy densities of 1–1018 kW/m^3 [1, 27]. Figure 1.2 depicts the mechanism of cavitation growth and collapse in liquid. The collapse takes place in microseconds and can be considered adiabatic. Cavitation can occur at millions of locations in a reactor simultaneously and generate conditions of very high temperatures and pressures (a few thousand atmospheres of pressure and a few thousand Kelvin of temperature) locally, while the overall environment remains at ambient conditions. As a result, chemical reactions that require stringent conditions can be effectively carried out using cavitation at ambient conditions.

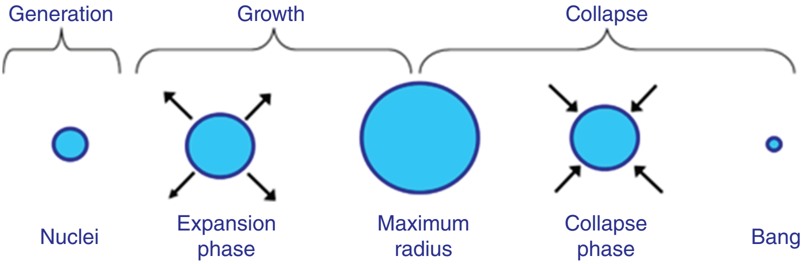

Figure 1.2 Mechanism of cavitation growth and collapse in liquid medium.

Acoustic cavitation is the process of nucleus growth and collapse of micro-gas bubbles or cavities in a liquid. This occurs rapidly, releasing large amounts of energy over a small area and creating extreme temperature and pressure gradients [23, 28, 29]. Cavitation generates high temperatures (between 1000 and 15 000 K) and pressures (between 500 and 5000 bar) locally and can occur at millions of locations within the reactor. Additionally, cavitation leads to acoustic streaming, intense shear stress near the collapsing bubble, and the formation of micro-jets. The local effects of cavitation are advantageous for reactions, including the generation of free radicals due to the dissociation of vapors trapped in the cavitating bubbles, which can intensify chemical reactions or cause unexpected reactions. The collapse of cavities also creates acoustic streaming and turbulence, promoting reaction rates [1, 13, 30]. Therefore, cavitation is useful for generating local turbulence and liquid micro-circulation and enhancing transport processes.

1.2.2 Types of Cavitation

Cavitation is a physical process that can happen when ultrasound is applied to a liquid medium, causing the formation, growth, and subsequent collapse of bubbles or voids in the liquid. The effects of ultrasound on the liquid medium can either be beneficial or detrimental, depending on the type of cavitation. Ultrasound radiation can stimulate various types of cavitation, such as stable cavitation, transient cavitation, inertial cavitation, and acoustic cavitation, depending on the properties of the liquid medium and the intensity and frequency of the ultrasound. To optimize ultrasound-based processes and minimize potential harmful effects, it is crucial to understand the different types of cavitation that can occur during US. The following are the various types of cavitation that can occur during US:

Stable cavitation: Stable cavitation occurs when bubbles are formed and oscillate in a liquid medium under the influence of ultrasound. Unlike other types of cavitation, the bubbles in stable cavitation do not collapse completely but rather oscillate at a specific frequency. The oscillation of these bubbles can generate acoustic streaming and microstreaming, which can enhance the mixing and mass transfer of the liquid medium. Stable cavitation has been utilized in several applications such as ultrasound-assisted emulsification, sonochemistry, and ultrasound-assisted extraction [31, 32].

Transient cavitation: Transient cavitation occurs when bubbles are formed, grow, and rapidly collapse in a liquid medium under the influence of ultrasound [33]. The collapse of these bubbles can produce high-pressure waves and shock waves, which can cause mechanical damage to cells and tissues. Although transient cavitation can be useful in applications such as sonoporation, which involves the temporary formation of pores in cell membranes to enhance drug delivery, excessive or prolonged exposure to it can result in tissue damage and cell death.

Inertial cavitation: Inertial cavitation occurs when bubbles in a liquid medium grow and collapse violently due to ultrasound exposure. The collapse of the bubbles produces high-pressure waves and shock waves that may result in mechanical damage to cells and tissues. Inertial cavitation can also create high temperatures and pressures that can trigger chemical reactions in the liquid medium [34]. This type of cavitation is usually unwanted in many applications due to the risk of tissue damage and chemical degradation.

Acoustic cavitation: Acoustic cavitation is a physical phenomenon that involves the formation and collapse of bubbles in a liquid medium under the influence of ultrasound. The type of cavitation can either be stable or transient, depending on the intensity of the ultrasound. Acoustic cavitation can produce high temperatures and pressures that can induce chemical reactions in the liquid medium, as well as generate free radicals and other reactive species that can cause chemical degradation.

Furthermore, cavitation can be categorized into four principal types, which are acoustic, hydrodynamic, optic, and particle cavitation, as illustrated in Figure 1.3. Acoustic and hydrodynamic cavitation is the result of tensions that exist in a liquid, while optic and particle cavitation arise from the local deposition of energy. The classification of cavitation based on the method of technique used and the process of cavity generation is important for understanding the effects of ultrasound on a liquid medium and for optimizing ultrasound-based processes.

Acoustic cavitation: Acoustic cavitation is the process of forming and collapsing bubbles in a liquid medium through the use of sound waves, particularly ultrasound with frequencies ranging from 16 kHz to 100 MHz. The phenomenon of chemical changes induced by acoustic cavitation is commonly known as sonochemistry [35]. It involves the combination of ultrasound and chemistry.

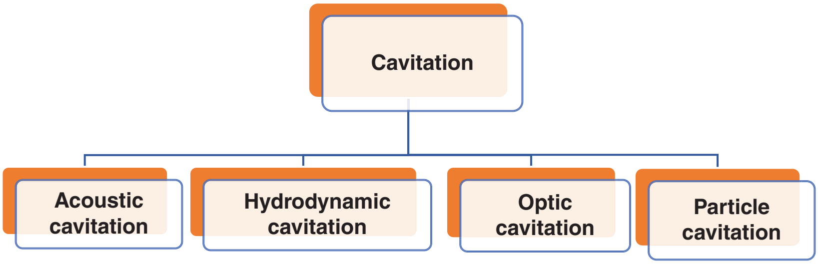

Figure 1.3 Types of cavitation based on technique used.

Hydrodynamic cavitation: Hydrodynamic cavitation is a type of cavitation that is produced by pressure variations created through the geometry of the system, which creates velocity variation. For instance, by leveraging the system's geometry, the interchange of pressure and kinetic energy can be achieved, leading to the formation of cavities, as seen in the case of flow through an orifice, venturi, and other similar systems.

Optic cavitation: Optic cavitation involves the use of high-intensity light, typically from a laser, to create cavitation in a liquid medium. The photons of the light can rupture the liquid continuum and generate bubbles or voids.

Particle cavitation: Particle cavitation is induced by a stream of elementary particles, such as a neutron beam, disrupting a liquid medium. This type of cavitation is commonly observed in devices like bubble chambers.

When it comes to cavitation, two types are frequently employed due to their efficacy in generating the necessary intensities for chemical or physical transformations: acoustic and hydrodynamic cavitation. The extent of cavitational impact hinges on both the turbulence intensity and the number of cavities formed. In essence, ultrasound wave propagation through medium results in acoustic cavitation, whereas hydrodynamic cavitation occurs as the flow's velocity changes due to alterations in the flow path geometry.

1.3 Application of Ultrasound Irradiation

US has a wide range of applications across various fields. Here are some notable applications of US:

Medical sciences: Ultrasound imaging is commonly used in medical diagnostics to visualize internal organs, tissues, and structures in real-time [36]. It is a noninvasive and radiation-free imaging technique that is particularly useful for examining the abdomen, pelvis, heart, blood vessels, and developing fetus during pregnancy (see Figure 1.4). There are some other applications, which are explained below.

Diagnostic imaging: One of the most common uses of ultrasound in medicine is diagnostic imaging. Ultrasound imaging allows noninvasive visualization of internal organs, tissues, and structures in real-time. It is used to examine various body parts, including the abdomen, pelvis, heart, blood vessels, musculoskeletal system, and the developing fetus during pregnancy [38, 39].

Obstetrics and gynecology: Ultrasound is extensively used in obstetrics and gynecology to monitor the progress of pregnancy, assess fetal development, determine the position of the fetus, and detect any abnormalities. It is also used for evaluating the female reproductive system, such as examining the uterus, ovaries, and fallopian tubes.

Cardiology: Ultrasound plays a crucial role in cardiology for evaluating the structure and function of the heart. Echocardiography, a type of ultrasound imaging, allows visualization of the heart's chambers, valves, and blood flow patterns.

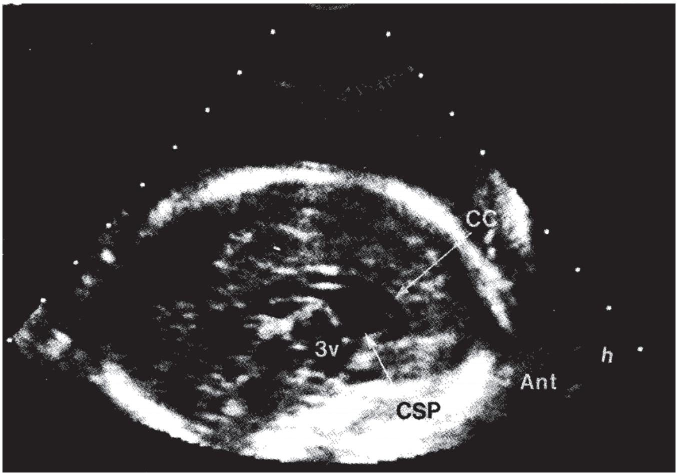

Figure 1.4 The abdominal sonography of the brain of a 21-week-old fetus. Source: Reproduced with permission from Pilu et al. [37]/John Wiley & Sons.

It helps in diagnosing and monitoring various heart conditions, such as heart valve disorders, congenital heart defects, and heart muscle abnormalities.

Vascular imaging: Ultrasound is used to examine blood vessels and assess blood flow patterns. Doppler ultrasound is particularly valuable in measuring the velocity and direction of blood flow, detecting blockages, or narrowing of vessels (such as in cases of deep vein thrombosis or arterial stenosis), and evaluating vascular abnormalities.

Interventional procedures: Ultrasound guidance is employed during certain minimally invasive procedures to enhance accuracy and safety. For example, ultrasound can be used to guide the insertion of needles for biopsies, aspirations, or injections. It helps in precisely targeting the intended area and avoiding damage to surrounding structures.

Sonography-guided therapies: Ultrasound is utilized in various therapeutic procedures. High-intensity focused ultrasound (HIFU) is used to precisely deliver focused energy to treat tumors or ablate abnormal tissues, such as uterine fibroids or prostate tumors, without the need for surgery. Additionally, ultrasound can be used for targeted drug delivery or gene therapy by utilizing microbubbles that enhance the permeability of cell membranes.

Guidance for minimally invasive surgeries: During minimally invasive surgeries, such as laparoscopic or robotic procedures, ultrasound can be used to provide real-time imaging guidance. It helps surgeons visualize and navigate internal structures, locate tumors or lesions, and ensure precise surgical instrument placement.

Therapeutic treatments: HIFU is utilized for therapeutic purposes. It involves focusing ultrasound waves on specific target tissues to generate heat or mechanical effects, leading to tissue ablation, tumor destruction, and targeted drug delivery. HIFU is used in the treatment of various conditions, including uterine fibroids, prostate cancer, liver tumors, and pain management.

Physiotherapy and rehabilitation: Ultrasound therapy is used in physiotherapy to provide deep tissue heating and promote healing. It is employed to treat conditions like muscle strains, sprains, joint inflammation, and sports injuries. The thermal effects of ultrasound can increase blood flow, relax muscles, and alleviate pain.

Dental applications: Ultrasound is utilized in dentistry for various procedures. It is commonly used for dental imaging, such as imaging the teeth and supporting structures. Ultrasonic scalers are also employed for dental cleanings and the removal of plaque and tartar from teeth.

Scaling and root planning, endodontic treatment, periodontal treatment, implantology, restorative dentistry, and dental prosthetics are important procedures to employ the ultrasonic iterations. Ultrasonic scalers are commonly used in dental hygiene for scaling and root planning procedures. These devices use ultrasonic vibrations to remove tartar, plaque, and bacterial deposits from the teeth and gums. The high-frequency vibrations generated by the ultrasonic scaler help to break down and dislodge the deposits, making the cleaning process more efficient and comfortable for the patient.

Ultrasonic instruments are utilized in endodontics, which involves the treatment of the tooth's pulp and root canal system. Ultrasonic tips, such as ultrasonic files or ultrasonic irrigators, are employed to remove infected or necrotic pulp tissue, clean and shape the root canals, and facilitate the irrigation of disinfectants or irrigation solutions. Ultrasonic vibrations aid in the removal of debris, disinfection of the canals, and better penetration of irrigants into complex root canal anatomy.

Ultrasonic devices are utilized in periodontal therapy to treat gum diseases and perform various procedures. Ultrasonic scalers and tips are used for subgingival debridement, which involves removing calculus and bacteria from below the gum line. The ultrasonic vibrations help to disrupt and remove the biofilm and tartar from periodontal pockets, promoting better healing and reduced pocket depths. Ultrasonic instruments are also employed in implant dentistry for the placement and maintenance of dental implants. During implant surgery, ultrasonic tips can be used for site preparation, osteotomy, and socket cleaning. Ultrasonic instruments are also useful for implant maintenance and cleaning around implant surfaces, removing plaque and calculus without damaging the implant or surrounding tissues.

The applications of ultrasonic irradiation in restorative dentistry procedures are as well. Ultrasonic instruments can be used for the removal of old restorative materials, such as amalgam or composite fillings, by gently vibrating and loosening the material for easier removal. Ultrasonic tips can also aid in the cleaning and preparation of the tooth structure before placing restorations like dental crowns or veneers.

1.3.1 Sonoluminescence and Sonophotocatalysis

Sonoluminescence refers to the emission of light from collapsing bubbles in a liquid medium under the influence of ultrasound. It is a fascinating phenomenon with potential applications in fields such as chemistry, physics, and materials

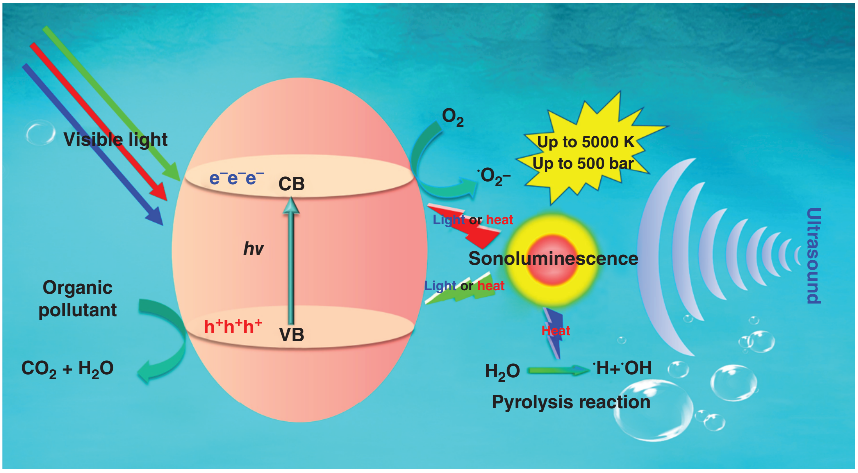

Figure 1.5 Schematic illustration for sonophotocatalytic mechanism. Source: Reproduced with permission from Wang and Cheng [40]/MDPI/Licensed under CC BY 4.0.

science. Sonophotocatalysis (see Figure 1.5) involves combining ultrasound with photocatalytic reactions to enhance the efficiency of photocatalysts for water treatment, pollution remediation, and energy production.

When used in conjunction with light and a photocatalyst, the sonophotocatalytic process can have a synergistic impact that speeds up the breakdown of organic contaminants in wastewater. The increased generation of reactive free radicals as well as the enhanced mass transfer of the contaminants to the photocatalyst surface are two reasons for the synergistic impact [40]. The enhanced creation of reactive radicals like $^{\cdot}OH$ (see Figure 1.5), which are particularly effective at destroying organic pollutants, is one of the main benefits of sonophotocatalysis. Ultrasonic waves have the ability to cause cavitation, which produces high-energy bubbles that burst and emit shockwaves and heat, leading reactive radicals to develop.

Yun et al. [41] have developed an efficient catalyst that can produce H_2O_2 and destroy refractory pollutants. This study uses an in situ precipitation technique to rationally construct a number of new $Ag_6Si_2O_7/SmFeO_3$ (ASF) heterojunction catalysts. Several characterization procedures were used to confirm the characteristics of the manufactured ASF nanocomposites. With an adequate concentration of ciprofloxacin (CIP) of 10 mg/l at 400 W US power, 0.6 g/l catalyst dosage, pH of 5.0, as well as 40 kHz US frequency during irradiation time of 60 minutes, the ASF-1.5 sample in particular displays high efficiency (94.9%) of sonophotocatalytic.

1.3.2 Industrial Cleaning

US is applied in industrial cleaning processes such as ultrasonic cleaning [42, 43]. It involves immersing objects in a cleaning solution and subjecting them to high-frequency sound waves. The cavitation effect generated by ultrasound helps remove dirt, contaminants, and deposits from the surfaces of objects, making it useful for cleaning delicate or intricate items.

Ultrasonic cleaning systems consist of a cleaning tank filled with a suitable cleaning solution or solvent. The object to be cleaned is immersed in the liquid, and ultrasonic transducers located in the tank generate high-frequency sound waves. These sound waves create alternating high- and low-pressure zones in the liquid, leading to the formation and collapse of cavitation bubbles near the object's surface. The collapse of these bubbles generates intense local energy, effectively scrubbing away contaminants.

Ultrasonic cleaning is highly effective in removing a wide range of contaminants, including oils, grease, dirt, rust, scale, and other residues [43]. The cavitation action reaches into complex geometries and crevices that are difficult to access using other cleaning methods. This makes it particularly useful for cleaning intricate parts, such as machine components, automotive parts, electronics, jewelry, medical instruments, and precision equipment.

One typical aspect of dairy processing is the ultrafiltration of whey solutions. The economics of such a process are, however, greatly impacted by the regular fouling of ultrafiltration membranes and the following cleaning cycle. In this study performed by Muthukumaran et al. [44], it is monitored into how ultrasonics affect the cleansing of whey-fouled membranes and what factors affect this result. A tiny single-sheet membrane unit that was completely submerged in an ultrasonic bath was used for the experiments.

An earlier solution to the problems produced by the acidic ammonium salt crystallization of vanadium was the ultrasound crystallization (UC) technique [45]. This study looked closely at how several parameters affected the properties of vanadium crystallization [45]. The results demonstrated that using ultrasonic power of 600 W, a baseline pH value of 2.0, ambient temperature of 95 °C, ammonium salt addition coefficient of 0.5, period of five minutes, excessive vanadium precipitation ratio (99.67%), and vanadium level of 20 g/l, along with V_2O_5 purity (99.50%) of the outcomes of the reaction can be achieved.

1.3.3 Material Processing

Ultrasound is used in various material processing applications. It can be employed for emulsification, dispersion, and homogenization of liquids, as well as particle size reduction. Ultrasonic devices are also used for degassing, degreasing, and defoaming processes in industries like food and beverage, pharmaceuticals, and cosmetics.

Ji et al. have studied the crystalline structures of Sn–Ag–Cu alloy ingots formed through ultrasound-assisted solidification, with an emphasis on the restrictions on ultrasonic processing depth and time imposed by the melt solidification's cooling rate [46]. Raising the ultrasonic power during cooling by air caused the –Sn phase to split from a dendritic structure into a circle-like equiaxed shape by lowering the undercooling temperature and lengthening the process of the solidification period. The grain size was reduced from 300 to 20 mm.

Using Y_2O_3, $CuCl_2$ as well as $BaCl_2$ as the starting components for the co-precipitation process, Jian-feng et al. [47] have produced Y_2BaCuO_5 nanocrystallites with the aid of ultrasonic irradiation. Transmission electron microscopy (TEM) and X-ray diffraction (XRD) were used to characterize the crystallization and morphologies of nanoparticles as prepared. Results demonstrate that using a mixture of NaOH and Na_2CO_3 as a precipitator, Y_2BaCuO_5 monophase can be produced at calcining temperatures up to 900 °C. With a rise in sonicating power, Y_2BaCuO_5 crystallites' particle size reduces. When the sonicating power is increased to 300 W, it is possible to produce Y_2BaCuO_5 crystallites that are around 30 nm in size.

In order to establish an affordable method for producing bioethanol, the effort focuses on intensifying delignification and subsequent enzymatic-hydrolysis of sustainable biomass such as coconut coir groundnut shells, and pistachio shells utilizing an ultrasound-aided methodology [48]. The obtained results for delignification of biomass showed that the extent of delignification for groundnut shells, coconut coir, and pistachio shells under conventional alkaline treatment was 41.8%, 45.9%, and 38%, respectively, while it raised to 71.1%, 89.5%, and 78.9%, providing a nearly 80–100% boost under the ultrasound supported technique. The traditional technique produced reducing sugar yields of 10.2, 12.1, and 8.1 g/l for groundnut shells, coconut coir, and pistachio shells, respectively, under optimal conditions. In contrast, the yields from ultrasound-assisted enzymatic hydrolysis were 21.3, 23.9, and 18.4 g/l in the identical amount of biomass.

1.3.4 Chemical and Biological Reactions

US is employed in chemical and biological reactions to enhance reaction rates, promote mixing, and improve mass transfer. It is used for various processes such as the synthesis of nanoparticles, extraction of bioactive compounds from plants, sonochemistry, and sono-organic reactions.

Although the use of ultrasound in biotechnology is still relatively recent, it has been found to trigger a number of mechanisms that happen when cells or enzymes are present [49]. The enzymes are denaturized, and the cells are broken by intense ultrasonic vibrations. Low-intensity ultrasonic waves have the ability to alter cellular metabolism or enhance the mass transfer of substances via the boundary layer, cellular membrane, or wall. The most significant aspect in the case of enzymes appears to be an increase in the mass transfer rate of the reagents to the active site. Native enzymes are more susceptible to the heat deactivation caused by ultrasound than immobilized enzymes. Enzymes can perform synthesis using reverse micelles. The use of ultrasound in biotechnology is considered in a number of applications. Molecular complexes stabilized by hydrogen bonding and dispersion interaction can also be studied [50–52]. Ngoc and colleagues conducted a study on the impact of ultrasound stimulation on hydrogen bonding within a composite slurry comprising networked alumina and polyacrylic acid.

Underwater communication and sensing: Ultrasound waves can travel long distances in water with minimal attenuation. This property makes ultrasound suitable for underwater communication and sensing applications [53, 54]. It is used for underwater navigation, fish finding, underwater imaging, and marine research. As a result of the Internet of Underwater Things (IoUT), new maritime commercial, scientific, and military applications will be possible. Since these systems are often powered by conventional batteries, powering electrical equipment in deep water still poses a significant difficulty. The first underwater sensor node without batteries has been designed by Guida et al. [53], and it can wirelessly recharge using ultrasonic waves over greater distances than are now possible. An undersea platform's architectural design that can draw electrical energy from ultrasonic waves is presented.

In a novel underwater self-powered all-optical wireless ultrasonic sensor (SAWS) that utilizes triboelectrification-induced electroluminescence (TIEL), Tian et al. [54] have demonstrated that accurate and persistent TIEL can be created under the excitation of ultrasonic waves. The SAWS has been shown to be an attractive option for real-time optical signal exchange because it has an ultrafast response time of below 50 ms and an ultrahigh signal-to-noise ratio (SNR) of 26.02 dB. It has also been demonstrated to precisely identify the exact position of the ultrasonic source with a margin of error of less than 4.6%.

Non-destructive testing: Ultrasound is employed in non-destructive testing (NDT) techniques to evaluate the integrity of materials and structures without causing damage [55, 56]. Ultrasound-based methods, such as ultrasonic testing (UT), are used for flaw detection, thickness measurement, and characterization of materials in industries like aerospace, automotive, and construction. Wire and Arc Additive Manufacturing (WAAM) parts are characterized using NDT techniques for materials techniques and inspection [56]. Electrical and ultrasonic tests were performed on the samples used to compare the techniques' capabilities. Metallographic, hardness, and electrical conductivity analysis were also applied to the same samples for product characterization.

Application of ultrasonic irradiation in synthesis: Nowadays, in the field of organic chemistry synthesis, ultrasonic irradiation techniques have been widely used, and are the most frequently used techniques among all the synthesis procedures. This is because of the fact that reaction rates can be improved, and one can adjust the selectivity performance of the reaction [57]. Ultrasonic irradiation techniques are considered to be the green synthetic process in chemistry, as this technique reduces the waste product, and less energy is required to carry out a reaction [58]. Microwaves (MW) and ultrasonic irradiation techniques are existing methods for process amplification and are being used both in industry and academy these days. Their mutual usage in the identical reactor led to significant consequences [59]. Ultrasonication permits the quick distribution of solids, the establishment of porous materials and nanostructures, and the decay of organics containing biological components [58]. Ultrasonic irradiation leads to the formation of particular reactive chemical species that cannot be produced from conventional conditions due to the physical and chemical effects of ultrasound. There are several advantages of this ultrasound irradiation technique over the conventional process for synthesizing organic compounds. The most important are higher percentage yield, selective product formation, easy generation of reactive species, and the usage of hazardous reagents. Ultrasonic irradiation techniques are used mainly for those organic synthesis reactions where traditional methods require very long reaction time and drastic conditions are required for initiating a reaction [60–62]. US procedure pathway is reported to have a strong influence on reaction rates, purity, as well as high yields in comparison to the conventional heating process [63]. Unique and proficient synthetic methods have been reported by Karmakar et al. for the formation of N/O-containing five- to seven-membered heterocycles and their fused analogs. Studies on chiral polymers have provoked excessive consideration between chiral supramolecular materials depending on their properties. The synthesis of chiral polymeric composites (CMNPs/1,4-Zbtb and 1,3-Zbtb) has been reported by Sharifzadeh et al. using solvothermal, mechanical stirring, and ultrasonic irradiation, three different methods. It has been found that synthesis carried out using ultrasound is much more proficient and also economically cost-effective than the other two methods. This process is also beneficial from an energy-saving and time-consuming point of view [64]. US techniques are also applied to minimize the waste going into the environment. Industrial solid waste (slag) obtained from the synthesis of catalysts contains SiO_2, Fe_2O_3, $Ca(OH)_2$, Al_2O_3, $CaCO_3$, and TiO_2 which can be dissolve using US [65]. Defective graphene nanosheets (dGN4V) having 5-9, 5-8-5, and point defects were synthesized using a sonoelectrochemical technique with an applied potential of 4 V (vs. Ag/AgCl) to initiate the rapid intercalation of phosphate ions amongst the layers of the graphite foil as a working electrode [66]. Synthesis of 1,5-dinitroaryl-1,4-pentadien-3-ones has been reported using US in the presence of K_2CO_3 as a catalyst [62]. For the green synthesis process, the ionic liquid is considered to be the best medium to carry out reactions in the microwave or ultrasonic irradiation [67]. Different compounds of 4,6-disubstituted-1,3,5-triazines series comprising hydrazone derivatives were synthesized using both ultrasonic irradiation and conventional heating methods. It has been observed that ultrasonication produces the required products of more yields, and of greater purity, in less time as compared to the normal conventional technique.

1.4 Conclusion

High frequency sound waves are used in the process of US to change the physical and chemical properties of materials. Applications for ultrasound can be found in a variety of disciplines, such as chemistry, material science, medicine, and food processing. The use of ultrasonic technology might theoretically result in greener and more intensified processing, which also saves a lot of money. US is a successful method to accelerate chemical reactions, improve yields, and shorten reaction times in chemistry and the chemical industries. Additionally, this method can be used to create composites, polymers, and nanoparticles, among other materials. US is used to process and modify materials in the field of material science, including surface cleaning, surface modification, and particle dispersion. Through the use of this technology, advanced materials with enhanced characteristics and performance have been created. US is frequently employed in medicine for therapeutic purposes such as tissue ablation and targeted medication distribution. US is useful in the food business for food processing and preservation, including compound extraction, food quality preservation, and texture enhancement. Overall, it has been demonstrated that cavitation has emerged as a key tool in a variety of industries with significant potential for environmentally friendly and sustainable processing. It is a promising instrument for the future because of its scope for improvement and development.

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