

Ultrasound-Assisted Chemistry: Principles and Application

Kalpana Jain¹, Pranali Satpute², Abhishek Yadav³, Sajid F. Shekh⁴,
Yashwant C. Gaikwad⁵, Chetana Tumade⁶

¹Professor and Principal, Royal College of Arts, Science & Commerce, Mira Road, Dist. Thane

²Student P.G. Department of Chemistry Veer Wajekar College Phunde, Uran

³Student U.G. Department of Chemistry Veer Wajekar College Phunde, Uran

⁴Incharge Principle of Anjuman Islam College, Murud

⁵Assistant Professor Department of Chemistry Veer Wajekar College Phunde, Uran

⁶Assistant Professor Department of Chemistry Veer Wajekar College Phunde, Uran

Abstract: *Sonochemistry involves the use of ultrasound to enhance chemical reactions and processes. The primary driving force behind sonochemical effects in liquids is acoustic cavitation, which involves the formation, expansion, and collapse of bubbles under ultrasonic irradiation. Unlike direct molecular interactions, the chemical effects of ultrasound arise from the extreme conditions generated during bubble collapse, leading to high temperatures and pressures that drive sonochemical reactions and sonoluminescence. Sonochemical processes can be carried out using either an ultrasonic bath, commonly employed for cleaning applications, or a high-power ultrasonic probe for more intensive reactions.*

Keywords: Sonochemistry, ultrasound, acoustic cavitation, bubble collapse, sonoluminescence, ultrasonic bath, high-power probe

I. INTRODUCTION

SONOCHEMISTRY

Sonochemistry is the branch of chemistry that explores the influence of ultrasonic waves on chemical systems. The chemical effects of ultrasound do not result from direct interaction with molecular species but are primarily driven by acoustic cavitation—the formation, growth, and implosive collapse of bubbles in a liquid medium. This phenomenon is responsible for processes such as ultrasound-induced sonication, sonoluminescence, and sonic cavitation (Suslick, 1989).

The first documented study on the effects of sonic waves in liquids was conducted by Robert Williams Wood (1868–1955) and Alfred Lee Loomis (1887–1975) in 1927. However, their work did not receive much attention at the time (Mason & Lorimer, 2002). Sonochemistry gained prominence in the 1980s with the development of high-intensity ultrasonic generators, making it easier to study and utilize ultrasound for chemical reactions.

When a liquid is irradiated with high-intensity ultrasound, acoustic cavitation occurs. This process—characterized by the formation, expansion, and collapse of bubbles—generates localized extreme conditions, leading to sonochemical reactions and sonoluminescence (Suslick, 1990). During bubble collapse, the rapid conversion of kinetic energy results in localized temperatures exceeding 5000 K, pressures reaching 1000 atm, and heating and cooling rates surpassing 10^4 K/s (Flint & Suslick, 1991). These extreme conditions allow for unique chemical transformations in an otherwise ambient environment.

In the presence of solids, ultrasound exposure leads to cavitation-induced effects such as high-speed jet formation and shock waves, which can erode solid surfaces or cause interparticle collisions in liquid-powder suspensions. Such collisions can modify surface morphology, composition, and reactivity (Mason, 1999). Depending on the medium, sonochemical reactions are classified into three categories:



1. **Homogeneous sonochemistry** of liquids
2. **Heterogeneous sonochemistry** of liquid-liquid or solid-liquid systems
3. **Sonocatalysis**, which overlaps with the first two (Suslick, 1998)

Sonoluminescence, a process where light is emitted during bubble collapse, is generally considered a specialized case of homogeneous sonochemistry (Flint & Suslick, 1991). The use of ultrasound has been shown to enhance reaction rates significantly, in some cases increasing chemical reactivity by a million-fold, effectively functioning as a catalyst (Mason, 2002). Furthermore, ultrasound enhances solid-phase reactions by breaking solids into finer particles, increasing their surface area and, consequently, reaction rates (Suslick et al., 1999).

Sonochemical reactions can be carried out using ultrasonic baths, commonly employed for cleaning purposes, or with high-power ultrasonic probes, which provide greater energy transfer to the reaction medium. The application of ultrasound in solution chemistry relies on acoustic cavitation, where alternating compression and rarefaction cycles lead to the formation of oscillating gas bubbles. These bubbles expand and eventually collapse, releasing energy that can trigger chemical reactions, material synthesis, and even biomedical applications (Gondrexon et al., 1997).

An example of a sonochemical reaction is the sonolysis of iron pentacarbonyl $[\text{Fe}(\text{CO})_5]$ in decane under argon. This reaction produces amorphous iron due to rapid decarbonylation. In contrast, using pentane as a solvent results in $\text{Fe}(\text{CO})_5$, indicating a slower bubble collapse rate (Suslick et al., 1986). Calculations suggest that bubble collapse in water can generate pressures exceeding 1000 atm and temperatures of several thousand Kelvin due to adiabatic heating, making cavitation bubbles act as microscale reaction vessels capable of driving unique and accelerated chemical transformations (Mason & Peters, 2002).

While basic sonochemical reactions can occur in ultrasonic cleaning baths, the energy reaching the reaction medium is typically between 1 and 5 W cm^{-2} , with poor temperature control. For large-scale applications, immersible ultrasonic probes are preferred, as they provide direct energy transfer, with applied energy levels hundreds of times higher than in ultrasonic baths (Margulis, 2001). Laboratory equipment generally operates within the 20–40 kHz range, though recent advancements have explored broader frequency ranges to optimize cavitation and reaction efficiency (Suslick, 2011).

II. SONOCHEMICAL REACTIONS

The following sonochemical effects can be observed in chemical reactions and processes:

Ultrasound has emerged as a powerful tool in chemical and materials processing due to its ability to significantly enhance reaction efficiency and modify reaction pathways. Its application can lead to a marked increase in reaction speed and overall output, while promoting more efficient energy usage. Ultrasound enables sonochemical methods that can switch reaction pathways, enhance the performance of phase transfer catalysts, or even allow reactions to proceed without the need for such catalysts. It also facilitates the use of crude or technical reagents, activates metals and solid materials, increases the reactivity of reagents or catalysts, improves particle synthesis, and allows for coating of nanoparticles. The specific effects of ultrasound in processes include the preparation of activated metals through reduction of metal salts, generation of activated metals via sonication, and the sonochemical synthesis of particles such as metal oxides (Fe, Cr, Mn, Co) for catalytic applications. Ultrasound is also employed for the impregnation of metals or metal halides on solid supports, preparation of activated metal solutions, and reactions involving metals through in situ generated organoelement species, as well as reactions involving non-metallic solids. Furthermore, ultrasound facilitates the crystallization and precipitation of metals, alloys, zeolites, and other solids, and enables



micromanipulation or fractionation of small particles. It is widely used for dispersing solids, preparing colloidal solutions such as Ag, Au, or quantum-sized CdS, and for intercalating guest molecules into host inorganic layered solids. Additionally, sonochemistry is applied in polymer chemistry to improve reaction efficiency, particle dispersion, and material properties. Overall, ultrasound serves as a versatile and efficient technique that enhances chemical reactivity, material processing, and synthesis in a variety of industrial and research applications.

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