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# Sonochemistry in nanocatalysis: the use of ultrasound from the catalyst synthesis to the catalytic reaction

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**Abstract:** This review succinctly describes the recent progresses in sonochemistry for the preparation of nanocatalysts as well as the use of ultrasound in organic reactions involving nanocatalysts. The main recent uses of power ultrasound in these fields reported here allow to determine some interesting trends and perspectives for this research, but also highlight some needs to innovate.

**Keywords:** sonochemistry; power ultrasound; nanocatalysis; materials; organic reactions.

## Introduction

Sonochemistry is the use of **power ultrasound** with frequencies between 20 kHz and 2 MHz (in opposition to diagnostic ultrasound particularly used in medical imaging with frequencies between 2 MHz and 200 MHz) to provide chemical, thermal and physical effects in solution [1]. The effects of ultrasound (intense local heat up to 5,000 K, very high pressure close to 1,000 bar, divergent shock waves, acoustic microcurrents and violet liquid microjets up to 100 m.s<sup>-1</sup>) are the consequence of the **cavitation phenomenon** (formation, growth and collapse of gaseous microbubbles in a liquid phase, phenomenon represented in Figure 1) [2]. The potential and applications of sonochemistry is directly connected to the choice of the sonochemical parameters. For example, the frequency is a crucial parameter and, in water, it is usually accepted that **low frequencies (20-80 kHz)** lead preferentially to physical effects (microconvection, shockwaves, microjets, etc) whereas at **high frequencies (150-2,000 kHz)** the chemical effects and the production of hydroxyl radical species (HO<sup>•</sup>) are favored. Conditions obtained in a medium submitted to power ultrasound are accountable for a large number of physico-chemical effects such as the increase in kinetics of chemicals reactions, changes in reaction mechanisms, emulsification effects, erosion, crystallization, precipitation, etc [3,4].

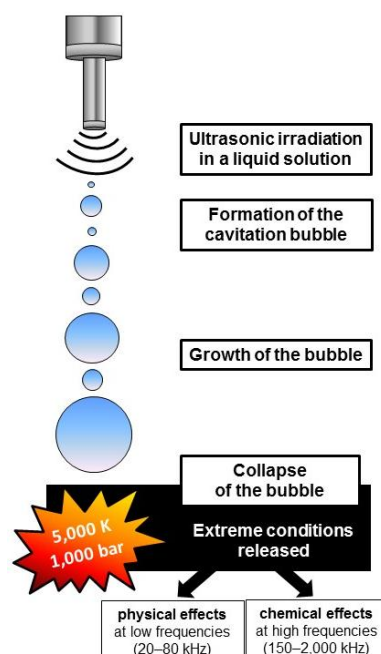


Figure 1: Cavitation phenomenon at the origin of the effects provided under power ultrasound.

Sonocatalysis, organic sonochemistry and sonochemical preparation of materials are the most investigated uses of power ultrasound these last decades, even if other applications in polymer chemistry, biomass valorization, extraction and environmental remediation also widely explored sonochemistry [5]. The scope of this review is limited to efforts of the last two years in the areas of **sononanocatalysis**, with one part of the studies **involving** ultrasound for the preparation of nanocatalysts and the other part applying ultrasound in organic reactions in the presence of a nanocatalyst.

### Sonochemical preparation of nanomaterials

The radical and mechanical effects of ultrasound have been widely investigated for the preparation of nanocatalysts or specific nanostructured materials. Suslick *et al.* reviewed in 2013 how ultrasound was used for the synthesis of nanostructured solids through different methods: **reduction from the solvent sonolysis** (Pt, Pd colloids), sonoelectrochemistry (metal colloids), spray pyrolysis and sonolysis of volatile organometals (zeolites, metal alloys, metal carbides/nitrides, sonogels, metal oxides, metal sulfides, semiconductors and exotic carbons) [6].

Recently, CO<sub>2</sub> reforming of CH<sub>4</sub> to produce hydrogen was investigated in the presence of bimetallic Ni-Co/Al<sub>2</sub>O<sub>3</sub>-MgO [7] and Ni-Co/Al<sub>2</sub>O<sub>3</sub>-ZrO<sub>2</sub> [8] nanocatalysts prepared under ultrasound at low frequency (20 kHz, immersed probe, Table 1, Entries 1 and 2). Authors reported that the irradiation of ultrasonic waves during impregnation process improves the morphology, specific surface area, **particles size distribution**, dispersion of metallic sites and consequently, **the catalytic activity** and anti-coking performance in the **dry reforming of methane**.

Fuel cell grade hydrogen was also produced *via* steam methanol reforming using CuO/ZnO/ZrO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> [9] and CuO/ZnO/CeO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> [10] nanocatalysts, synthesized by sonochemical coprecipitation at low frequency (Table 1, Entries 3 and 4). The FESEM (Field Emission Scanning Electron Microscope) images described that the nanocatalysts had nanometer particles which became smaller by increasing the ultrasound power from 30 W to 90 W (electric output). Low frequency ultrasound also prevented the Cr/clinoptilolite catalyst deactivation during the synthesis [11,12]. The same advantages were highlighted for the preparation of sono-sulfated zirconia nanocatalyst supported on MCM-41 (Table 1, Entry 6) [13].

Palladium oxide (PdO) nanoparticles deposited on silica nanoparticles [14], NiFe<sub>2-x</sub>Eu<sub>x</sub>O<sub>4</sub> nanostructured catalysts [15], CoFe<sub>2</sub>O<sub>4</sub>/B<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> magnetic composite nanostructure [16], sulfuric acid-functionalized silica-based magnetic core/shell nanocomposite [17], and Cu<sub>2</sub>O-nanocubes heterogeneous nanocatalyst [18] were synthesized and studied in fine chemistry applications, showing better catalytic activity, better yields, shorter reaction times, the possibility to easily recover the catalyst and presenting some advantages at an environmental point of view (Table 1, Entries 9-11).

Interestingly, it seems that the coated nanomaterials (with capping agents such as polyvinyl pyrrolidone, phenolics, etc) are not negatively impacted by ultrasonic irradiation. On the contrary, some examples noted that the coating is stable and cannot be removed by a **simple washing procedure with water, or ethanol and/or acetone after an ultrasonic treatment** [19].

Other recent applications reported from the use of ultrasonic prepared nanocatalysts are about photodegradation of dye and pollutants in aqueous effluents [20-22]. **Interesting researches proposed to combine ultrasonic and solar light irradiations as degradation processes based on well defined metal-supported nanoparticles** [23,24]. Sonophotodeposition (ultrasound and light radiations) and sonoelectrodeposition (ultrasound and electrical fields) processes have been also recently shown **synergetic actions in the syntheses of different nanomaterials for photodegradation steps** [25].

**Table 1:** Recent examples of sonochemical preparation of nanocatalysts.

| Entry | Nanocatalyst                              | Experimental conditions                            | Applications of the catalyst   | Advantages described by the authors   | Ref. |
|-------|---|--|--|---|------|
| 1     | Ni-Co/Al <sub>2</sub> O <sub>3</sub> -MgO | 20 kHz (probe), 90 W, 45 min, temp. not controlled | CO <sub>2</sub> reforming of CH <sub>4</sub> for hydrogen production | Enhancement of the dispersion of active phase and surface area in comparison with impregnation method | [7]  |

|    |   |  |  |   |      |
|----|---|--|--|---|------|
| 2  | Ni-Co/Al <sub>2</sub> O <sub>3</sub> -ZrO <sub>2</sub>  | 20 kHz (probe), 30-90 W, 20-80 min, temp. not controlled             | CO <sub>2</sub> reforming of CH <sub>4</sub> for hydrogen production | Improvement of the morphology, specific surface area, particle size distribution, dispersion of metallic sites and catalytic activity | [8]  |
| 3  | CuO/ZnO/ZrO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>  | 20 kHz (probe), 30-90 W, 45 min, temp. not controlled                | Steam MeOH reforming for hydrogen production                         | Decrease of copper and zinc oxides crystallinity. Surface area enhancement  | [9]  |
| 4  | CuO/ZnO/CeO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>  | 20 kHz (probe), 30-90 W, 5-15 min, temp. not controlled              | Steam MeOH reforming for hydrogen production                         | Improvement of the homogeneity and reduction of particles size  | [10] |
| 5  | Cr/clinoptilolite-ZrO <sub>2</sub>  | 20 kHz (probe), 90 W, 60 min, temp. not controlled                   | CO <sub>2</sub> -dehydrogenation of ethane                           | Reduction of the formation of Cr <sub>2</sub> O <sub>3</sub> and decrease to nanometer scale the chromium particles                   | [11] |
| 6  | S-ZrO <sub>2</sub> /MCM-41  | 20 kHz (probe), 30-90 W, 30 min, temp. not controlled                | Biodiesel production from sunflower oil                              | Improvement of the morphology, particle size, surface area and particle distribution compared to non-sonicated sample                 | [13] |
| 7  | PdO doped silica nanoparticle   | 20 kHz (probe), 80 W.cm <sup>-2</sup> , 15 min, temp. not controlled | Selective aerobic alcohol oxidation                                  | Uniform size and shape. Preservation of the crystalline structure without agglomeration.  | [14] |
| 8  | NiFe <sub>2-x</sub> Eu <sub>x</sub> O <sub>4</sub>  | 20 kHz (probe), 65 W, 10 min then 70 W, 30 min, temp not controlled  | Synthesis of benzimidazoles, benzoxazoles, and benzothiazoles        | Decrease of the particle size and increase of surface area.   | [15] |
| 9  | CoFe <sub>2</sub> O <sub>4</sub> /B <sub>2</sub> O <sub>3</sub> -SiO <sub>2</sub>                                       | 40 kHz (bath), 250 W (max), 1 h, 60 °C                               | Synthesis of dihydroquinolinones                                     | Increase of the catalytic activity  | [16] |
| 10 | Fe <sub>3</sub> O <sub>4</sub> /SiO <sub>2</sub><br>Fe <sub>3</sub> O <sub>4</sub> /SiO <sub>2</sub> -SO <sub>3</sub> H | 40 kHz (bath), 250 W (max), 1 h, 60 °C                               | Synthesis of nitroaromatic compounds                                 | Reduction of particles size. Increase of the catalytic activity   | [17] |
| 11 | Cu <sub>2</sub> O-nanocubes   | 20 kHz (pulse mode 5s/5s) 15 min, temp. not controlled               | Synthesis of quinazolines  | Increase of the catalytic activity  | [18] |
| 12 | CdO-ZnO nano-photocatalyst  | 20 kHz (probe), 90 W, 45 min, temp. not controlled                   | Removal of acid orange 7 from wastewater                             | Better results in both morphological characterization analyses and photocatalytic performance experiments                             | [20] |
| 13 | martite nanocatalyst  | 36 kHz (bath), 150 W, 30 min, temp. not controlled                   | Treatment of a textile dye   | Increase of the catalytic activity  | [21] |
| 14 | Ag/AgFeO <sub>2</sub> nanocatalyst  | 45 kHz (bath), 100 W, 0.5-20 min, temp. not controlled               | Typical azo dye photodegradation                                     | Enhancement of the photocatalytic performances  | [22] |

### Sonochemistry in the presence of nanocatalysts

Several reviews have covered the large scale of applications of ultrasound in sonocatalysis [5,26,27, 28]. Generally, it is difficult to clearly identify the real effects brought by ultrasound irradiation and to exactly understand and prove how it can affect the reactivity. However, the main consequences observed are interesting such as an improvement of yield, selectivity or rate, reduction of reaction time, and sometimes a change in the mechanistic pathway [5].

Recently, a study compared an ultrasonic-assisted catalytic transesterification using ZnO nanocatalyst with the conventional stirring method (Table 2, Entry 1). In the sonochemical method, 96% of yield was achieved at constant temperature and reaction time was reduced from 1 h to 15 min. The properties of the obtained biodiesel from both methods showed many similarities [29].

Table 2 reports the studies of the studies from the literature using ultrasound as activation methods for catalytic organic reactions, in the presence of a nanocatalyst [30-39]. In all these cases, only low ultrasonic frequencies (19.5 to 40 kHz) were used *via* an immersed probe or a cleaning bath. The consequences of the use of ultrasound were the same in all the studies: (i) the reaction time was drastically reduced (4-45 min) compared to silent conditions; (ii) the conversion and the yield were improved; (iii) the reaction was performed at low temperature and pressure (generally ambient). These results have been explained by the effects of mechanochemical energy or micromixing and emulsification effects, both provided by cavitation [40].

**Table 2:** Recent examples of sonochemical reaction performed in the presence of nanocatalysts.

| Entry | Nanocatalyst   | Experimental conditions           | Reaction/applications                          | Advantages reported by authors  | Ref. |
|-------|--|-----------------------------------|--|---|------|
| 1     | ZnO  | 32 kHz (bath), 15 min, 60 °C      | Transesterification for biodiesel production   | Better yields and higher conversion efficiency. Reaction time significantly reduced | [29] |
| 2     | CuFe <sub>2</sub> O <sub>4</sub>                     | 20 kHz (probe), 30-60 W, 4-10 min | Synthesis of pyrido[2,3-d:6,5-d']dipyrimidines | Excellent yields, high purities and short reaction times                            | [30] |
| 3     | Fe <sub>3</sub> O <sub>4</sub> /Ph-SO <sub>3</sub> H | Low frequency (bath), 10-50 min,  | Synthesis of tetrahydrobenzo[b]pyrans          | Excellent results were obtained at room temperature and short time                  | [31] |

|    |   |   |   |  |      |
|----|---|---|---|--|------|
|    |   | room temperature                                  |   |  |      |
| 4  | Fe <sub>3</sub> O <sub>4</sub> / 4,5-imidazolecarboxylic acid   | 37 kHz (probe), 150 W, 5-12 min, room temperature | Synthesis of benzimidazoles   | High yields, low reaction times, and easy catalyst workup by an external magnetic field  | [32] |
| 5  | Fe <sub>3</sub> O <sub>4</sub>  | 20 kHz (probe), 180 W, 45 min, 60°C               | Synthesis of secondary amides <i>via</i> Beckmann rearrangement                   | Simplicity, excellent yields, mildness and eco-friendly aspects of the synthetic protocol  | [33] |
| 6  | Fe <sub>3</sub> O <sub>4</sub> /PEG/succinic anhydride  | No frequency indicated, 60 W, 15-35 min           | Synthesis of benzoxanthenes.  | Easy work-up, short reaction times, recycling of the catalyst, little catalyst loading   | [34] |
| 7  | Fe <sub>3</sub> O <sub>4</sub> /SiO <sub>2</sub> -CO-C <sub>6</sub> H <sub>4</sub> -NH <sub>2</sub>   | 40 kHz, 250 W, 3x30 min,                          | Multicomponent synthesis of pyridoimidazoisoquinolines                            | Easy workup procedure, recyclability of the heterogeneous nanocatalyst by an external magnet   | [35] |
| 8  | Fe <sub>3</sub> O <sub>4</sub> /clay core/shell nanocomposite   | 40 kHz (bath), 250 W, 15 min, room temperature    | Synthesis of imidazo(thiazolo) pyrimidines  | Avoiding hazardous organic solvents and toxic catalysts, easy work-up procedure, short reaction times, excellent yields and mild reaction conditions | [36] |
| 9  | Multiwall carbon nanotubes/TiO <sub>2</sub>   | 40 kHz (bath), 250 W, 15-20 min, room temperature | Selective conversions of alcohols and alkenes to aldehydes, ketones and epoxides. | Easy workup procedure, excellent conversion and yields, short reaction times and mild reaction conditions  | [30] |
| 10 | CoFe <sub>2</sub> O <sub>4</sub>  | 40 kHz (bath), 770 W, 40 °C, 20-30 min            | Synthesis of 2,4,5-trisubstituted imidazoles                                      | Very fast, green and low-cost procedure  | [35] |
| 11 | SBA-SO <sub>3</sub> H   | 19.5 kHz (probe), 600 W, 8-25 min, 90-140 °C      | Synthesis of imidazoles   | Enhancement of the mass transfer with no need to anchor, confine or embed an additional hydrophobic group or ionic liquid                            | [36] |
| 12 | Cu/TiO <sub>2</sub>   | 24 kHz (probe), 400 W, 8-12 min                   | Multicomponent synthesis of 1,4-disubstituted 1,2,3-triazoles in water            | Reduction of the reaction time and temperature   | [37] |
| 13 | Fe <sub>2</sub> O <sub>3</sub> @SiO <sub>2</sub> -(CH <sub>2</sub> ) <sub>3</sub> NHC(O)(CH <sub>2</sub> ) <sub>2</sub> PPh <sub>2</sub> organic-inorganic core-shell nanomagnetic catalyst | 40 kHz (bath) 250 W, 11 min                       | Synthesis of tetrazolo[1,5-a]pyrimidine derivatives                               | Easy workup procedure, excellent yields and mild reaction conditions.  | [38] |
| 14 | MgFe <sub>2</sub> O <sub>4</sub>  | 20 kHz (probe), 35 W, 10-30 min, 45 °C            | Knoevenagel condensation  | Mild reaction conditions, excellent yields and short reaction times  | [39] |

Some recent examples also reported the use of heterogeneous nanocatalysts for environmental remediation applications, testing their sonocatalytic [41-45] and sonophotocatalytic activities [46] for the degradation of pollutants in liquid effluents. In these recent examples, low ultrasonic frequencies have been used allowing the reduction of treatment times. The difference with other examples of catalytic organic reaction is the difference of initial concentration in substrate, very low in the case of degradation processes (only traces of pollutants to degrade until total mineralization).

### Conclusions, perspectives and recommendations:

Interestingly, the majority of the studies reported during these two last years has been published in the Elsevier journal *Ultrasonics Sonochemistry*. It is logical that studies involving power ultrasound in chemistry processes are published in this thematic and specialize journal, especially dedicated to the community of sonochemists. However, it could be also interesting to communicate in journals with more general audience of chemists to demonstrate the potential of ultrasound for all the areas of chemistry. Indeed, it is important to remember that ultrasound is not just a *simple mixing tool*, but a **real innovative technology** that can lead to results never obtained in classical conditions.

In conclusion, Table 1 shows that ultrasonic probes are mainly used (direct irradiation) compared to ultrasonic baths (indirect irradiation), probably to benefit from the sufficient power of irradiation and improve the physical effects provided by low frequency ultrasound. Generally, it was clearly reported that, under ultrasound, treatment times are reduced and performance of the nanocatalysts are improved. In addition, the main physical effects of ultrasound are from the high-speed jets and intense shock waves induced by cavitation. Enhanced mass transfer as a consequence of acoustic streaming and bulk thermal heating is another physical effect of ultrasound used in the preparation

of nanomaterials [47]. Physical effects of ultrasound can also be used to promote the diffusion of dopant ions into spherical nanoparticles [48].

However, the control of the temperature during the process is not often performed. The rigorous control of temperature conditions during the ultrasonic irradiation is crucial to clearly identify the effects of ultrasound in the preparation of a catalyst, but also in terms of reproducibility of its syntheses.

Table 2 shows the advantages of ultrasound for applications in fine chemistry and production of fuels, in addition of the studies about the degradation of pollutants. In all these cases, the reaction times are very short (10-30 min in average) and the energy consumption is low, compared to silent conditions, showing some interesting advantages in term of green chemistry. The contribution of sonochemistry to green chemistry have been recently discussed, based on the advantageous consequences obtained under ultrasound [49]: better yields and selectivities, reduced reaction times, new reactivity, use of water as solvent, increasing or optimization of the reactivity in the presence of catalysts, dispersion and reduction of particles, etc.

However, in the recent examples, no data on the real acoustic power dissipated in the sonochemical reactor has been reported. Only electric powers indicated by the generator (provided by the constructor) have been specified. It is clearly recommended to systematically report an estimation of the dissipated ultrasonic power and energy costs, to energetically compare the systems with each other. As an industrial point of view, the overall energy consumption of a sonochemical process is also essential.

A last, from a theoretical point of view, investigations on mechanisms are also required to better understand and use of sononanocatalysis in order to really benefit from the entire potential of ultrasound. The research only based on "is better than" is not sufficient at this stage: new clues and new proofs are clearly necessary for advances in the area.

#### Competing interests statement:

The author declares having no competing interests.

#### References:

1. Mason TJ: **Sonochemistry**. Oxford University Press: Oxford, 1999, 92 p.
2. Suslick KS, Hammerton DA, Cline DE: **Sonochemical hot spot**. *J. Am. Chem. Soc.* 1986, **108**: 5641–5645.
3. Mason TJ: **Sonochemistry and sonoprocessing: the link, the trends and (probably) the future**. *Ultrason. Sonochem.* 2003, **10**: 175–179.
4. Cravotto G, Cintas P: **Forcing and controlling chemical reactions with ultrasound**. *Angew. Chem. Int. Ed.* 2007, **46**: 5476–5478.
5. Chatel G: **Sonochemistry – New opportunities for Green Chemistry**. World Scientific: London, 2017, 170 p.
6. Xu H, Zeiger BW, Suslick K: **Sonochemical synthesis of nanomaterials**. *Chem. Soc. Rev.* 2013, **42**: 2555–2567.
7. Abdollahifar M, Haghghi M, Babaluo AA, Talkhonchek SK: **Sono-synthesis and characterization of bimetallic Ni–Co/Al<sub>2</sub>O<sub>3</sub>–MgO nanocatalyst: Effects of metal content on catalytic properties and activity for hydrogen production via CO<sub>2</sub> reforming of CH<sub>4</sub>**. *Ultrason. Sonochem.* 2016, **31**: 173–183.
- 8.\* Mahboob S, Haghghi M, Rahmani F: **Sonochemically preparation and characterization of bimetallic Ni–Co/Al<sub>2</sub>O<sub>3</sub>–ZrO<sub>2</sub> nanocatalyst: Effects of ultrasound irradiation time and power on catalytic properties and activity in dry reforming of CH<sub>4</sub>**. *Ultrason. Sonochem.* 2017, **38**: 38–49. Authors showed that longer and more intense ultrasonic irradiations are in the preparation of Ni-Co/Al<sub>2</sub>O<sub>3</sub>-ZrO<sub>2</sub> catalyst, more helpful in deagglomerating and dispersing nanoparticles with limited growth and consequently, enhancing catalytic performance.
9. Ahmadi F, Haghghi M, Ajamein H: **Sonochemically coprecipitation synthesis of CuO/ZnO/ZrO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> nanocatalyst for fuel cell grade hydrogen production via steam methanol reforming**. *J. Mol. Catal. A.* 2016, **421**: 196–208.
10. Hosseini T, Haghghi M, Ajamein H: **Fuel cell-grade hydrogen production from methanol over sonochemical coprecipitated copper based nanocatalyst: Influence of irradiation power and time on catalytic properties and performance**. *Energy Conv. Manag.* 2016, **126**: 595–607.

- 
11. \*Rahmani F, Haghighi M, Mahboob S: **CO<sub>2</sub>-enhanced dehydrogenation of ethane over sonochemically synthesized Cr/clinoptilolite-ZrO<sub>2</sub> nanocatalyst: Effects of ultrasound irradiation and ZrO<sub>2</sub> loading on catalytic activity and stability.** *Ultrason. Sonochem.* 2016, **33**: 150–163. In addition to the positive effects of Cr dispersion increasing and the decrease of submicron particle size of chromium to nanometer scalar over the catalyst surface, low frequency ultrasound also prevented the Cr/clinoptilolite catalyst desactivation during the synthesis leading the authors to speak about of *synergistic effects* when ultrasound is used
  12. Sene RA, Moradi GR, Sharifnia S: **Sono-dispersion of TiO<sub>2</sub> nanoparticles over clinoptilolite used in photocatalytic hydrogen production: Effect of ultrasound irradiation during conventional synthesis methods.** *Ultrason. Sonochem.* 2017, **37**: 490–501.
  13. Dehghani S, Haghighi M: **Sono-sulfated zirconia nanocatalyst supported on MCM-41 for biodiesel production from sunflower oil: Influence of ultrasound irradiation power on catalytic properties and performance.** *Ultrason. Sonochem.* 2017, **35**: 142–151.
  14. Seok S, Hussain MA, Park KJ, Kim JW, Kim DH: **Sonochemical synthesis of PdO@silica as a nanocatalyst for selective aerobic alcohol oxidation.** *Ultrason. Sonochem.* 2016, **28**: 178–184.
  15. Ziarati A, Sobhani-Nasab A, Rahimi-Nasrabadi, Reza Ganjali M, Badiei A: **Sonication method synergism with rare earth based nanocatalyst: preparation of NiFe<sub>2-x</sub>Eu<sub>x</sub>O<sub>4</sub> nanostructures and its catalytic applications for the synthesis of benzimidazoles, benzoxazoles, and benzothiazoles under ultrasonic irradiation.** *Ultrason. Sonochem.* 2016, **28**: 178–184.
  16. Maleki A, Aghaei M, Hafizi-Atabak H, Ferdowsi M: **Ultrasonic treatment of CoFe<sub>2</sub>O<sub>4</sub>@B<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> as a new hybrid magnetic composite nanostructure and catalytic application in the synthesis of dihydroquinazolinones.** *Ultrason. Sonochem.* 2017, **37**: 260–266.
  17. Maleki A, Aghaei M.: **Ultrasonic-assisted environmentally-friendly synergetic synthesis of nitroaromatic compounds in core/shell nanoreactor: A green protocol.** *Ultrason. Sonochem.* 2017, **37**: 260–266.
  18. Raut AB, Tiwari AR, Bhanage BM: **Ultrasonic irradiation assisted preparation of Cu<sub>2</sub>O-nanocubes and their high catalytic activity in synthesis of quinazolines.** *ChemCatChem.* 2017, **9**: 1292–1297.
  19. Applerot G, Perkas N, Amirian G, Girshevitz O, Gedanken A: **Coating of glass with ZnO via ultrasonic irradiation and a study of its antibacterial properties.** *Appl. Surf. Sci.* 2009, **256S**: S3 – S8..
  20. Margan P, Haghighi M: **Sono-coprecipitation synthesis and physicochemical characterization of CdO-ZnO nanophotocatalyst for removal of acid orange 7 from wastewater.** *Ultrason. Sonochem.* 2018, **40**: 323–332.
  21. Dindarsafa M, Khataee, Kaymak B, Vahid B, Karimi A, Rahmani A: **Heterogeneous sono-Fenton-like process using martite nanocatalyst prepared by high energy planetary ball milling for treatment of a textile dye.** *Ultrason. Sonochem.* 2017, **34**: 389–399.
  22. Tang D, Zhang G: **Ultrasonic-assistant fabrication of cocoon-like Ag/AgFeO<sub>2</sub> nanocatalyst with excellent plasmon enhanced visible-light photocatalytic activity.** *Ultrason. Sonochem.* 2017, **37**: 208–215.
  23. Colmenares JC, Magdziarz A, Lomot D, Chernyayeva O, Lisovytskiy D.: **A new photocatalytic tool in VOCs abatement: Effective synergetic combination of sonication and light for the synthesis of monometallic palladium-containing TiO<sub>2</sub>.** *Appl. Catal. B: Environ.* 2014, **147**: 624–632.
  24. Colmenares JC, Magdziarz A, Chernyayeva O, Lisovytskiy D, Kurzydowski K, Grzonka J: **Sonication-Assisted Low-Temperature Routes for the Synthesis of Supported Fe–TiO<sub>2</sub> Econanomaterials: Partial Photooxidation of Glucose and Phenol Aqueous Degradation.** *ChemCatChem.* 2013, **5**: 2270–2277.
  25. Magdziarz A, Colmenares JC: **In situ coupling of ultrasound to electro- and photo-deposition methods for materials synthesis.** *Molecules.* 2017, **22**: 216–238.
  26. Luche JL: **Synthetic organic sonochemistry.** Plenum Press : New-York, 1998, 392 p.
  27. Cravotto G, Borretto E, Oliverio M, Procopio A, Penoni A: **Organic reactions in water of biphasic aquos systems under sonochemical conditions.** *Catal. Commun.* 2015, **63**: 2–9.
  28. Kuna E, Behling R, Valange S, Chatel G, Colmenares JC: **Sonocatalysis: A Potential Sustainable Pathway for the Valorization of Lignocellulosic Biomass and Derivatives.** *Top. Curr. Chem.* 2017, **375**: 41–61.
  29. Varghese R, Henry JP, Irudayaraj J: **Ultrasonication-assisted transesterification for biodiesel production by using heterogeneous ZnO nanocatalyst.** *Environ. Prog.* 2018, **37**: 1176–1182.
  30. Naeimi H, Didar A: **Efficient sonochemical green reaction of aldehyde, thiobarbituric acid and ammonium acetate using magnetically recyclable nanocatalyst in water.** *Ultrason. Sonochem.* 2017, **34**: 889–895.
  31. Elhamifar D, Ramazani Z, Norouzi M, Mirbagheri R: **Magnetic iron oxide/phenylsulfonic acid: A novel, efficient and recoverable nanocatalyst for green synthesis of tetrahydrobenzo[b] pyrans under ultrasonic conditions.** *J. Coll. Inter. Sci.* 2018, **511**: 392–401.

- 
32. Hosseini MS, Ghafuri H, Zand HRE: **4,5-Imidazoledicarboxylic acid immobilized on Fe<sub>3</sub>O<sub>4</sub> magnetic nanoparticles: Preparation, characterization, and application as a recyclable and efficient nanocatalyst in the sonochemical condensation reaction.** *J. Chin. Chem. Soc.* 2018, 1–6.
  33. KarimKoshteh M, Bagheri M: **Nano Fe<sub>3</sub>O<sub>4</sub> as green catalyst for beckmann rearrangement under ultrasound irradiation.** *J. Mex. Chem. Soc.* 2017, **61**: 28–34.
  34. Safaei-Ghomi J, Eshteghal F: **Nano-Fe<sub>3</sub>O<sub>4</sub>/PEG/succinic anhydride: A novel and efficient catalyst for the synthesis of benzoxanthenes under ultrasonic irradiation** *Ultrason. Sonochem.* 2017, **38**: 488–495.
  - 35.\* Eidi E, Kassae MZ, Nasresfahani Z: **Synthesis of 2,4,5-trisubstituted imidazoles over reusable CoFe<sub>2</sub>O<sub>4</sub> nanoparticles: an efficient and green sonochemical process.** *Appl. Organomet. Chem.* 2016, **30**: 561–565. Effects of solvents (DMSO, acetonitrile, EtOH, water, methanol, dimethylformamide) in the presence of low frequency ultrasound was studied in the synthesis of 2,4,5-trisubstituted imidazoles with CoFe<sub>2</sub>O<sub>4</sub> nanoparticles. Interestingly, other experimental parameters were tested such as power intensity, temperature, time and amount of catalyst on the model reaction.
  36. Doustkhah E, Rostamnia S, Hassankhani A: **The raise of SBA-SO<sub>3</sub>H catalytic activity by inducing ultrasound irradiation in the multicomponent syntheses.** 2016, **23**: 549–556.
  37. Alyari M, Mehrabani MG, Allahvirdinesbat M, Safa KD, Kafil HS, Panahi PN: **Ultrasound assisted synthesis of thiazolidine thiones containing 1,2,3-triazoles using Cu/TiO<sub>2</sub>.** *Arkivoc.* 2017, **iv**: 145–157.
  38. Maleki A, Rahimi J, Demchuk OM, Wilczewska AZ, Jasinski R: **Green in water sonochemical synthesis of tetrazolopyrimidine derivatives by a novel core-shell magnetic nanostructure catalyst.** *Ultrason. Sonochem.* 2018, **43**: 262–271.
  - 39.\*Ghomi JS, Akbarzadeh Z: **Ultrasonic accelerated Knoevenagel condensation by magnetically recoverable MgFe<sub>2</sub>O<sub>4</sub> nanocatalyst: A rapid and green synthesis of coumarins under solvent-free conditions.** *Ultrason. Sonochem.* 2018, **40**: 78–83. In this study, the synthesis of 3-substituted coumarins by Knoevenagel condensation of salicylaldehydes and 1,3-dicarbonyl compounds was performed in the presence of magnetically recoverable MgFe<sub>2</sub>O<sub>4</sub> nanoparticles under ultrasound irradiation. Interestingly, an ultrasonic probe (20 kHz) was used to increase the acoustic power delivered in the medium. The catalyst was recycled several times and analyzed through SEM images before and after reuse of six times.
  40. Cravotto G, Cintas P: **Power ultrasound in organic synthesis: moving cavitation chemistry from academia to innovative and large-scale applications.** *Chem. Sci.* 2012, **10**: 175–307.
  41. Li G, Zhang H, Wei C, Huang Y, Dou X, Wang Y, Wang J, Song Y: **Preparation of (5.0%)Er<sup>3+</sup>:Y<sub>3</sub>Al<sub>5</sub>O<sub>12</sub>/Pt-(TiO<sub>2</sub>-Ta<sub>2</sub>O<sub>5</sub>) nanocatalysts and application in sonocatalytic decomposition of ametryn in aqueous solution.** *Ultrason. Sonochem.* 2017, **34**: 763–773.
  42. Siadatnasab F, Farhadi S, Khataee A: **Sonocatalytic performance of magnetically separable CuS/CoFe<sub>2</sub>O<sub>4</sub> nanohybrid for efficient degradation of organic dyes.** *Ultrason. Sonochem.* 2018, **44**: 359–367.
  43. Khataee, Mohamadi FT, Rad TS, Vahid B: **Heterogeneous sonocatalytic degradation of anazolene sodium by synthesized dysprosium doped CdSe nanostructures.** *Ultrason. Sonochem.* 2018, **40**: 361–372.
  44. Sajjadi S, Khataee A, Kamali M: **Sonocatalytic degradation of methylene blue by a novel graphene quantum dots anchored CdSe nanocatalyst.** *Ultrason. Sonochem.* 2017, **39**: 676–685.
  45. Bhuyan B, Paul B, Purkayastha DD, Sankar Dhar S, Behera S: **Facile synthesis and characterization of zinc oxide nanoparticles and studies of their catalytic activity towards ultrasound-assisted degradation of metronidazole.** *Mater. Lett.* 2016, **168**: 158–162.
  46. Dinesh GK, Anandan S, Sivasankar T: **Synthesis of Fe-doped Bi<sub>2</sub>O<sub>3</sub> nanocatalyst and its sonophotocatalytic activity on synthetic dye and real textile wastewater.** *Environ. Sci. Pollt. Res.* 2016, **20**: 20100–20110.
  - 47.\*\* Valange S, Chatel G, Amaniampong PN, Behling R, Jérôme F: **Ultrasound-assisted synthesis of nanostructured oxide materials: basic concepts and applications to energy, In: Advanced solid catalysts for renewable energy production** (Eds. González-Cortés S, Imbert FE). IGI Global: Hershey PA, USA, 2018, 530 p. This recent book chapter emphasizes the use of high-intensity ultrasound as a powerful tool for the production of nanostructured materials through sonochemical synthesis or ultrasonic spray pyrolysis. The chapter shows that the peculiar physico-chemical properties of such ultrasound-assisted synthesized oxide materials allow them to be highly efficient in various renewable energy applications.
  48. Xiong HM, Shchukin DG, Mohwald H, Xu Y, Xia YY: **Sonochemical synthesis of highly luminescent zinc oxide nanoparticles doped with magnesium(II).** *Angew. Chem. Int. Ed.* 2009, **48**: 2727–2731.
  49. Chatel G: **How sonochemistry contributes to green chemistry?** *Ultrason. Sonochem.* 2018, **40**: 117–122.