A power-triggered preparation strategy of nano-structured inorganics: sonosynthesis

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Ultrasound irradiation covers many chemical reactions crucially aiming to design and synthesize various structured materials as an enduring trend in frontier research studies. Here, we focus on the latest progress of ultrasound-assisted synthesis and present the basic principles or mechanisms of sonosynthesis (or sonochemical synthesis) from ultrasound irradiation in a brand new way, including primary sonosynthesis, secondary sonosynthesis, and synergetic sonosynthesis. This current review describes in detail the various sonochemical synthesis strategies for nano-structured inorganic materials and the unique aspects of products including the size, morphology, structure, and properties. In addition, the review points out the probable challenges and technological potential for future advancement. We hope that such a review can provide a comprehensive understanding of sonosynthesis and emphasize the great significance of structured materials synthesis as a power-induced strategy broadening the updated applications of ultrasound.

1. Introduction

Ultrasound, which is industrially generated from electrical energy by using a magnetostrictive or piezoelectric transducer, often serves as a driving force to facilitate many physical, mechanical or chemical processes. Generally, high-frequency ultrasound is typically used in medical applications for diagnosis and therapy, e.g., to aid in drug delivery, to break down blood clots, or even to destroy tumors in surgery. By comparison, low-frequency ultrasound is widely used in research and industry to efficiently clean the debris from surfaces, to purify water from degrading contaminants, to initiate reduction, oxidation and hydrolysis reactions, or to accelerate crystallization and polymerizations. For example, sonolysis or ultrasonic catalysis, as one of the advanced

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oxidation processes (AOPs), has been exploited for the degrada-
tion of toxic organics in order to protect the aqueous envi-
ronment, where ultrasound irradiation combined with other
AOPs and/or oxidizing agents can enhance the reaction rate,
decrease the processing conditions, and reduce the overall
energy consumption.12,13 Fig. 1 lists the general applications of
low-frequency ultrasound in chemistry, material, engineering
and manufacturing fields, and many processes refer to the
checmical effects from ultrasound. As for the chemical effects
from ultrasound irradiation, the precise term “sonochemistry”
is coined, covering a special research area where powerful
ultrasound induces chemical reactions or even merely partici-
pates in some chemical processes as a nonclassical method.14,15
Actually, since ultrasonic equipment came into being, the
chemical effects from ultrasound or sonochemistry-based
applications have been reported,16 and especially, more and
more ultrasound-assisted methods have emerged in synthetic
chemistry, organometallic chemistry, material chemistry, biol-
ogical chemistry, medical chemistry, etc.17–23

Inorganic materials have attracted much attention owing to
their unique structures and/or properties and widespread
applications in many fields ranging from catalysis, hydrogen
storage, and energy storage to the sensors, electronics,
bioelectronics and nanomedicine, and correspondingly,
numerous methods have been developed for their synthesis,
such as the coprecipitation method, sol-gel method, and sol-
vothermal method.24–27 So far, many sonochemical preparation
methods including a few combined strategies with the aid of
ultrasound irradiation have been also carried out to create
inorganic materials, where ultrasound irradiation seems to be
a power-inducing preparation source. Recently, we have pub-
lished a review paper on the catalytic applications of
ultrasound-synthesized inorganic nano-materials, and the
content highlighted sonochemistry applications in the
inorganic-based catalysis processes including reduction,
oxidation, degradation, polymerization, etc.4 In contrast, this
review will provide an overview on the latest developments of
the ultrasound-assisted synthesis of nano-structured inor-
ganics, where more emphasis is put on the matters about the
sonothesis (or sonochemical synthesis), wherein it will
provide a fundamental understanding of the basic principles of
sonothesis including acoustic cavitation, sonochemistry,
and physical/mechanical effects and will present the nano-scale
inorganic materials produced by the sonochemistry-inducing
synthesis, as well as the size, morphology, structure, and
properties of products. Moreover, the review will point out the
prospective challenges and trends in sonothesis-assembled
programming of miscellaneous materials, broaden the
synthetic methodology, and conclude the significance of sono-
thesis in abundant applications.

2. Mechanism of sonothesis

For either low-frequency or high-frequency ultrasound, sono-
synthesis is a conventional representation for chemical reac-
tions. Theoretically, there is no direct interaction at least in
a molecular level between ultrasound and chemical species,
since some typical index values of sound wave are much larger
than the molecular scale in a liquid system, e.g., sound velocity
(1000–1500 m s−1) and sound wavelength (10−6 to 10−1 m).28,29
In comparison to other energy sources such as heat, light and
microwave, ultrasonic irradiation can offer some extreme
transient conditions (e.g., localized high pressure and tempera-
ture) by acoustic cavitation and bring up some interesting
chemical effects on the synthesis processes,30 or taken as
a whole, the sonochemistry as well as the derivative sono-
synthesis originates from acoustic cavitation primarily.

Acoustic cavitation, namely the continuous changing states
of cavitation bubbles including the formation, growth, and
violent collapse, is a transient process caused by irradiating
a liquid with ultrasound.31 The ultrasound, as a conventional
pressure wave, can cause the liquid medium to experience an
alternate compression and rarefaction phase when moving
forward, and the particles in the liquid will respond to the
acoustic pressure cycles, resulting in sound propagation.
During the rarefaction phase (or negative-pressure) cycle, the
liquid is pulled apart at some sites containing some gaseous
impurities (known as “weak spots”) by overcoming intermo-
lecular interactions and the cavitation bubbles are usually

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nucleated at the “weak spot” sites. Once formed, the bubbles can keep trapped in the acoustic pressure field and grow through a rectified diffusion process owing to the contributing area and shell effect. The average surface area of cavitation bubbles during the rarefaction phase is larger than during the compression phase, so there is always a gas flow into the bubbles over several cycles. Meanwhile, the gas inflow is always higher during the expansion stage because the diffusion rate into the cavity should be proportional to the concentration gradient of solvent vapor and dissolved gas, so such a concentration gradient in the fluid shell around the bubbles also contributes to the bubble growth in volume. When the bubbles grow up to a critical size range (typically tens of micrometers), they will be no longer stable and undergo a rapid inertial overgrowth by coupling strongly to the acoustic field, and subsequently, a catastrophic collapse occurs at some point. During the cavitation, the compression of oscillating bubbles accumulating ultrasonic energy effectively leads to an enormous energy concentration being stored within a small volume. The concentrated energy will be released from the bubbles within a very short time (estimated 3.5 µs) via an implosive collapse that is a nearly adiabatic process, and thus, acoustic cavitation can result in the formation of a localized micro-scale “hotspot” which experiences high temperature (up to thousands of degrees) and high pressure (over hundreds of atmospheres). Fig. 2 gives us the schematic illustration of hotspot formation under acoustic cavitation. The intensity of acoustic cavitation, largely determining the rate and/or productivity of sonochemistry, can be simultaneously influenced by the ambient conditions (e.g., dissolved gases, solvent, reaction temperature, and hydrostatic pressure) and the device parameters (e.g., ultrasonic frequency and acoustic power), and the inductive description can be presented as follows: (1) the dissolved gases significantly act as the “weak spot” sites in a liquid, but the bubbling gases can produce more cavitation bubbles through the mixture, and the type of bubbling gases is important as well; for instance, the gas with a higher specific heat ratio should give a greater cavitation effect, while the gas with a larger solubility provides more nucleation sites for cavitation. (2) The cavities may be more readily formed when a solvent has higher vapor pressure, lower viscosity and surface tension, but the one with opposing characteristics benefits the cavitation intensity, so an optimum solvent is able to dominate the cavitation. (3) In a certain system, an increasing ambient temperature may lead to more favorable results, but has a negative effect on the sonochemical effects, namely, higher ambient temperature results in easier bubble formation, whereas the bubbles containing more vapors receive an overall decrease in the cavitation. (4) Contrary to the temperature, enlarging the ambient pressure of the system generally leads to a predominant increase in acoustic cavitation as a result of the decrease in vapor pressure. (5) Ultrasonic frequency can alter the critical size of the formed cavitation bubbles, and low frequency produces more violent cavitation with higher localized temperature and pressure. (6) When a continuously advancing ultrasonic power is delivered to the reaction system, the acoustic cavitation will increase to a maximum and then decrease probably because the dense cavitation bubbles formed near the probe tip at high power acts to block the energy transmitted from the probe to the fluid.

To date, several competing theories have been postulated to explain the chemical effects created by ultrasound irradiation, but most of them are completely discarded as a valid mechanism of sonoluminescence and sonochemistry. Since the acoustic cavitation accounts for the transient characteristic conditions, hotspot theory has become more generally accepted, where it highlights that the extreme conditions from the localized hotspots will form a few active species for the follow-up sonochemistry. In a system, the bulk of the liquid has no direct sonochemical events, but the compressional heat released from collapsing bubbles generates enough high temperatures effectively and locally inducing the dissociation of chemical bonds, and the induced radicals may diffuse into the liquid prior to further reactions. Primary sonochemistry refers to the indiscernible processes that result in the formation of radical species from the volatiles and/or gases inside the collapsing bubble. In the bubble center (Fig. 3), namely at the hotspots, the harsh conditions can cause the sonolysis reaction.
to occur, where the gases present in the bubbles (Zone 1) or in the interfacial region (Zone 2) between the bubble center and bulk liquid will experience large gradients of temperature, pressure, and shear. As a powerful tool to understand the origin of the drastic conditions created by acoustic cavitation, the analysis of sonoluminescence spectra from water under power ultrasound reveals the overpopulation of OH(A2Σ+) vibrational levels, indicating the formation of non-equilibrium plasma inside the cavitation bubbles.40 The non-equilibrium plasma is the major state of gas inside violently collapsing cavitation bubbles. Based on a two-site model for the sonochemical regions, most of the radical production is thought to occur in the interior vapor phase when the liquid layer immediately surrounding the cavitation bubbles bursts into the bubbles upon the cavitation collapse. Moreover, the primary sonochemical effect relates to the cavitation bubble types. The transient cavitation bubble often grows to a large size quickly and collapses after one acoustic cycle, which accounts for most of the chemical activity in the system. The stable cavitation bubble can persist for more acoustic cycles and create a large shear gradient when it collapses, where the shear force plays an important role in a sonochemical system, e.g., the emulsification caused by the cavitation is significant to allow an efficient preparation of polymer microspheres.41

Different from primary sonochemistry, secondary sonochemistry involves that the initial species formed in the primary sonochemical stage migrate into the surrounding liquid and suffer from a variety of reactions with solutes (Zone 3). In the well-studied case of sonicating aqueous liquids (Fig. 4), the fragmentation of water can generate highly active hydrogen radicals (H+) and hydroxyl radicals (‘OH) (reaction 1), which has been captured photographically by using a luminol solution to enhance the blue sonochemiluminescence generated near the cavitation bubbles.42 Upon diffusing out, these H+ and ‘OH radicals can combine to produce hydrogen (H2) and hydrogen peroxide (H2O2) (reactions (2) and (3)) if taking no account of their recombination to be an original form or can also generate secondary radicals (R’) (reaction 4) by reacting with organic additives (e.g., 2-propanol or ethanol) or produce hydroperoxyl radicals (HO2•) by combining with dissolved oxygen (O2) (reaction 5). Either the strong oxidants or reductants are used to initiate various chemical reactions in an aqueous or nonaqueous solution including the reductions, oxidation, hydroxylation of organics, etc.43 Like the acoustic cavitation, the generation of radicals strongly depends on a great number of factors. Take ultrasound frequency as an example, the production of active species stays at a very low level under a low-frequency ultrasound even though the collapse of larger cavitation bubbles creates stronger shear forces, and with the frequency enhancing, the production rates increase quickly up to a maximum at 300–800 kHz and then drop off, where the shear force decreases considerably.

For many materials synthesis or other relevant events, the sonochemical processes of solvents or solutes serve as an excitation source and induce some catalysis or sonosynthesis which is a power-inducing preparation strategy. Besides, ultrasound irradiation often gives rise to numerous physical effects (e.g., simple heating, shock waves and microjets) accompanied by the chemical consequences, and these factors are able to order the sonosynthesis performance in materials synthesis by affecting the frequency and efficiency of chemical reactions.44 During sonication, the typical ultrasonic horns deliver acoustic energy into the liquid, changing into heat, which can be useful for activating reactive atoms or molecules, accelerating dissolution and facilitating crystallization. The microjets occur due to the asymmetrical collapse of highly energetic bubbles in any heterogeneous system, and they can lead to the modification of surfaces (pitting and erosion) or the generation of surface nanostructures.45,46 Shock waves will be created if a bubble unperturbed by the surface rebounds rapidly from its minimum spherical radius causing the compression of the surrounding liquid to propagate outwards.47 The shock waves can induce several different mechanical, physical or chemical consequences, e.g., increasing the mass transport due to strong turbulent mixing and acoustic streaming, accelerating solid particles suspended in the liquid, and inducing changes in size distributions, morphologies and surface compositions owing to the enhanced interparticle collisions. Additionally, the mechanical effects (e.g., shear force, interparticle collisions, rapid mixing, and turbulence) from ultrasound irradiation are also important in the chemical consequences. Anyhow, the applications of sonosynthesis almost cover the chemical, physical and/or mechanical effects, for example, the fragmentation for brittle materials, the emulsification for immiscible liquids, the agglomeration for malleable materials, the exfoliation of layered materials into 2D layers, and even the fabrication and delivery of drug systems.48,49

| 20 kHz Ar | 20 kHz Ar/O2 |
|---|---|
| H2O → H+ + •OH | (1) |
| 2H+ → H2 | (2) |
| 2•OH → H2O2 | (3) |
| RH + •OH (or H+) → R+ + H2O (or H2) | (4) |
| H+ + O2 → HO2• | (5) |

Fig. 4 Sonochemiluminescence (left) observed in a luminol solution (pH 11.0, Na2CO3) under ultrasound irradiation (20 kHz, 33 W), in which the sonoysis of water involves several rapid primary and secondary reactions (right). Reproduced with permission.42 Copyright 2018 American Chemical Society.

3. Synthesis of inorganic nanomaterials

So far, the synthesis of inorganic nanomaterials has been explored with a view to the nature of precursors, the structures and properties of products and the feasibility and simplification
of methods. For instance, Sun et al. successfully prepared a GdMnO₃ material using a typical sol–gel method and subsequently in situ generated GdMn₂O₃/GdMnO₃ materials by acid treatment for complete oxidation of oxygenated VOCs. Tan et al. synthesized TiO₂−x/W₁₈O₄₉ with core–shell or double-shelled hollow microspheres through a facile multi-step solvothermal method, where the advanced architecture significantly enhanced the electronic properties of TiO₂−x/W₁₈O₄₉ for CO₂ photo-reduction efficiency. Deng and co-workers fabricated TiO₂ supported Pt nano-/single-atom catalysts by using the molten salt method, and 0.2 wt% Pt catalyst showed high catalytic activity for toluene removal. Our team once created superparamagnetic ferroferric oxide nanoparticles by the coprecipitation method and then yielded hydrophilic or hydrophobic targeting biomaterials by a few modifications. As a supplementary choice, ultrasound irradiation provides a facile route for the synthesis of the nanomaterials, mainly attributed to primary sonosynthesis, secondary sonosynthesis and synergistic sonosynthesis, where primary sonosynthesis is based on primary sonocatalysis when secondary sonosynthesis widely employs the secondary sonocatalytic consequences. Many inorganics including metals, alloys, metal compounds (e.g., metal oxides, metal sulfides, and metal nitrides), and nonmetals (e.g., carbon materials, silicon materials, and selenium materials) have been yielded from the precursors, widely covering a variety of structures such as solid structures, hollow structures, core–shell structures, porous structures, nanotube structures, nanorod structures, and layered structures (Fig. 5).

4. Primary sonosynthesis

Primary sonosynthesis derives from the case that the implosive collapse of cavitation bubbles releases the stored energy within a very short time in a nearly adiabatic way so that the surrounding solvent or solutes experience high temperature inducing the breakage of chemical bonds. Some cases on the primary sonosynthesis have been summarized in Table 1. Directly, such sonosynthesis sometimes does not involve the quadratic transformation of active species. A few volatile organometallic compounds in a nonvolatile solvent such as silicone oil or long-chain hydrocarbons can cause the dissociation of organic groups and the release of individual metal atoms under ultrasound irradiation. Under argon gas, the sonication of Fe(CO)₅ in an alkane solvent or ionic liquid with a low vapor pressure efficiently yielded a black porous iron powder with traces of residual carbon and oxygen at the freezing point. In the process, the atoms of the organometallic compound were thermally excited to the point where visible light was emitted analogous to the emission from flame excitation. Certainly, the nonvolatile solvents were needed because the additional vapor had to absorb the available energy in the collapsing bubble in order that the achieved conditions were much less extreme. Because the metal atoms were so rapidly cooled that crystallization was prevented within a short-lifetime cavitation event, the obtained product appeared to be an agglomeration of 20 nm amorphous nanoparticles. Other metal precursors with single or multiple ligands like Cr(CO)₆, Ni(CO)₄, and Co(CO)₅NO also have produced amorphous porous metal nanoparticles, even obtaining alloy nanoparticles by varying the composition in the solution.

Under the high-temperature conditions provided by the hotspots, the metal atoms decomposed from volatile organometallic compounds are highly active and can react with dissolved gas in the solvent to form new nanomaterials, for example, Mo(CO)₆ in hexadecane and W(CO)₆ in diphenylmethane by sonocatalytically heating under CH₄/H₂ gas separately led to the formation of nanostructured MoₓC or WₓC/C porous aggregates, and the products showed superior activity, selectivity and stability for the dehydrogenation and/or hydrodehalogenation of organic pollutants. Alternatively, some metal nitrides or metal oxides were also produced when the sonication of metal carbonyl compounds occurred under a reductive NH₃/H₂ gas mixture or in the presence of air. Under ambient air of 80 °C, Argiriusis et al. used organic solvents containing the precursors W(CO)₆ or Mo(CO)₆ to sonocatalytically prepare metal oxide nanoparticles on anode materials and revealed that the size distribution and morphology of nanoparticles responded to ultrasound intensity and solvents when their decoration loading extent on substrates was affected by ultrasound intensity/duration as well as the ratio of precursor and substrate compounds. Interestingly, Zavala-Rivera et al. carried out the sonocatalytic reaction of Fe(CO)₅ in octanol under an inert air condition or pure oxygen condition using low-intensity ultrasound with a frequency of 40 kHz and finally obtained iron carbide@iron oxide nanoparticles composed of an iron carbide core and a magnetite shell. Based on the core–shell structure, researchers concluded a possible sonosynthesis mechanism that the formation of the iron oxide layer occurred via the secondary interaction of iron carbide and oxygen followed by the decarbonization of Fe(CO)₅ to produce the nucleation points of iron carbide with the aid of oxygen.

The sonocatalytically released metal atoms are also able to react with other solutes or even solvent molecules. When the Fe atoms were released from the Fe(CO)₅ precursors under ultrasound irradiation, individual smaller iron nanoparticles with 8 nm diameter would be created if oleic acid or other similar

![Fig. 5 A variety of inorganic nanomaterials based on sonocatalysis.](image-url)
surfactants were present in the solvent to stabilize the metal atoms. To prepare the coated iron nanoparticles, Nikitenko et al. reported the sonochemical decomposition of iron carbonyl indiphenylmethane, where an air-stable magnetic powder was formed after annealing the as-prepared sample at 973 K in argon. The nanoparticle structure featured a core–shell geometry consisting of an Fe₃C layer (about 3 nm thickness) on the top of a crystallized Fe core, and the ratio of Fe to Fe₃C was close to 4 : 1. Other core–shell transition metal nanoparticles have been also created in the similar way, but some syntheses were usually particular and limited. In an ultrasound process reported by Suslick et al., adding elemental sulfur to the 1,2,3,5-tetramethylbenzene containing Mo(CO)₆ produced clustered MoS₂ nanoparticles with a higher edge.

Table 1  Synthesis based on the primary sonocatalysis

| Precursor | Product | Experimental parameters under ultrasound | Ref. |
|-----------|---------|----------------------------------------|------|
| Fe(CO)₅  | Porous iron | Decane, Ar atmosphere, 20 kHz, 100 W cm⁻², sonication for 3 h | 54 |
| Mo(CO)₆  | Mo₂C    | Hexadecane (50 mL), Ar atmosphere, 20 kHz, 100 W cm⁻², 90 °C, sonication for 3 h | 56 |
| W(CO)₆  | WₓC/C   | Diphenylmethane (50 mL), 20 kHz, 600 W, 32 W cm⁻², 80 ± 2 °C, sonication for 30 min | 57 |
| Fe(CO)₅  | Fe₂₋₅N  | Decane, NH₃/H₂ (3 : 1), 20 kHz, 100 W cm⁻², 0 °C, sonication for 4 h | 58 |
| W(CO)₆ or Mo(CO)₆ | WOₓ or MoOₓ | Diphenylmethane and decalin (100 mL), ambient air, 20 kHz, 200 W, 80 °C, sonication for 3 h | 59 |
| Fe(CO)₅  | Iron carbide@iron oxide core–shell nanoparticles | Oleic acid, 1-octanol (5 mL), 40 kHz, room temperature, sonication for 40 min | 60 |
| Fe(CO)₅  | Iron colloid of Fe/FeO | Oleic acid, hexadecane, Ar atmosphere, 40 kHz, 30 °C, sonication for 1 h | 61 |
| Mo(CO)₆  | Clustered MoS₂ nanoparticles | Elemental sulfur, 1,2,3,5-tetramethylbenzene, Ar atmosphere, 20 kHz, 80 W cm⁻², 80 °C, sonication for 1.5 h | 62 |
| Cu(CH₃COO)₂·H₂O, Co(NO₃)₂·6H₂O, Ni(NO₃)₂·6H₂O, CuCl₂ | Nano-sized Cu(n), Co(n) and Ni(n) complexes | Ahpv ligand, ethanol (10 mL), 24 kHz, 400 W | 63 |
| Pb(NO₃)₂ | [Pb(L)(SCN)]₂₋₅ | l-Methylimidazole [L], KSCN, methanol, 60 W, 30 °C, sonication for 30 min | 64 |
| Gallium  | Ga@C-dots | Decane, dodecane, hexadecane or polyethylene glycol, 20 kHz, 750 W, 30 °C or 60 °C, sonication for 3–180 min | 65 |
| Mo(CO)₆  | MoOₓ-coated silica nanoparticles, hollow MoS₂ | Silica spheres, elemental sulfur, isodurene, Ar atmosphere | 66 |
| Co₄(CO)₁₂ | Porous Co₃O₄ | Carbon nanotubes, hexane, sonication for 0.5 h | 67 |
| Fe(CO)₅  | Hollow hematite | Carbon nanoparticles, hexadecane (40 mL), argon flow, 20 kHz, 50 W cm⁻², 20 °C, sonication for 3 h | 68 |
| Si₃H₈   | Silicon nanoparticles | N₂-filled atmosphere with residual traces of H₂O and O₂ (~1 ppm), 26 kHz, 32–130 W cm⁻², 1–4 W, 25–40 °C, sonication for 2 min | 69 |
| p-Xylene | Single-walled or multi-walled carbon nanotubes | Silica powder, ferrocene, p-xylene solution (50 mL), pulsed 65% at 200 W, atmospheric pressure, room temperature, sonication for 20 min | 70 |
| Dopamine hydrochloride | Nitrogen-doped carbon quantum dots | Dimethylformamide (150 mL), 20 kHz, 600 W, sonication for 8 h | 71 |
surface area under argon gas, and such MoS2 nanoparticles substantially exhibited high catalytic activity for the hydrodesulfurization of thiophene. Abdel-Rahman et al. once synthesized a Schiff base ligand (ahpv) by the condensation of 3-methoxysalicylaldehyde and 2-amino-3-hydroxypyridine and then added it dropwise to the ethanol solutions of different metal salts (i.e., Cu(CH3COO)2·H2O, Co(NO3)2·6H2O, and Ni(NO3)2·6H2O) positioned under high-density ultrasound irradiation, preparing nano-sized Cu(II), Co(II) and Ni(II) complexes of ahpv. Abdel-Rahman et al. once synthesized a Schiff base ligand (ahpv) by the condensation of 3-methoxysalicylaldehyde and 2-amino-3-hydroxypyridine and then added it dropwise to the ethanol solutions of different metal salts (i.e., Cu(CH3COO)2·H2O, Co(NO3)2·6H2O, and Ni(NO3)2·6H2O) positioned under high-density ultrasound irradiation, preparing nano-sized Cu(II), Co(II) and Ni(II) complexes of ahpv. Rayan et al. obtained another nano-sized Schiff base ligand copper complex [Cu(L)(H2O)Cl] by using the sonochemical route, where L was 2-((pyridin-3-ylmethylene)amino)phenol prepared by the condensation of 3-pyridinecarboxaldehyde with 2-aminophenol. In a study of Hayati et al., novel metalorganic coordination polymer compounds were fabricated with the aid of the sonochemical process, in which l-methylimidazole (L), KSCN and Pb(NO3)2 were used to synthesize [Pb(L)(SCN)2]n by a branch tube method under high-density ultrasound. Gedanken et al. applied ultrasound irradiation of molten gallium in various organic liquids to produce some identified nanometric gallium particles, e.g., gallium spheres coated with a carbon film when gallium was sonicated in decane, dodecane and hexadecane, precipitated gallium particles coated with C-dots and supernatant gallium-doped C-dots during the sonication of gallium in polyethylene glycol. After investigating the nature of the product, they found that the ultrasound irradiation of molten gallium immersed in organic liquids caused the partial decomposition of the hydrocarbon medium prior to the interaction between carbon and gallium. In addition, a removable template (e.g., SiO2 nanoparticles or microspheres) present can give an aid to the produced free metal atoms to directly deposit onto the support when sonication of the volatile organometallic precursors, forming different structured materials. Under the air, the ultrasound irradiation of Mo(CO)6 and silica nanoparticles in 1,2,3,5-tetramethylbenzene yielded MoO3-coated silica nanoparticles which would leave hollow MoO3 behind by using HF to etch the silica component, and instead, adding elemental sulfur into the system and replacing the air with Ar gas could form hollow MoS2 (Fig. 6). Except the SiO2 materials, carbon nanoparticles and organic ligands can also serve as a sacrificial template to inorganic nanomaterials. The sonochemical product of Co4(CO)12 in the presence of carbon nanotubes would not be amorphous cobalt but porous Co3O4, where the carbon nanotubes as a template spontaneously removed themself via the combustion attributed to the rapid oxidation of elemental Fe upon air exposure. In a similar fashion, the precursor Fe(CO)5 also could produce hollow hematite when carbon nanoparticles were employed as a template.

In addition, nonmetal precursors are able to facilely and highly produce amorphous nanomaterials by the sonosynthesis effects. Bedini et al. carried out the sonochemical synthesis of...
silicon nanoparticles,\textsuperscript{72} where the trisilane (Si\textsubscript{3}H\textsubscript{8}) solution underwent the sonication process in an inert N\textsubscript{2} atmosphere with residual traces of H\textsubscript{2}O and O\textsubscript{2}. The as-synthesized silicon nanoparticles were discrete, hydrogenated, and non-crystalline. Therefore, the isolated formation of nanoparticles was attributable to the interplay among the extreme conditions during bubble collapse and the high density of active species (e.g., silicon radicals) created at such spatially localized points (Fig. 7), while the amorphous morphology was ascribed to the residual bonded hydrogen in the particles due to incomplete diffusion during the short-lived collapse and the proposal that the silicon matrix did not have enough interaction time to reconstruct into a crystalline state. The silicon nanoparticles had a tunable size in the range of 1.5–50 nm, which could be controlled by varying the ultrasound amplitude or the trisilane concentration. Researchers found that low ultrasound amplitude or low trisilane concentration favored the generation of discrete and monodisperse silicon nanoparticles, which might be attributed to smaller microbubbles and/or less trisilane diffusion during bubble growth. Correspondingly, high amplitude and high trisilane concentration produced large amounts of larger and more polydisperse particles. In the absence of any templates or surfactants, the sonication of amorphous selenium colloids in alcohol could thermodynamically form trigonal selenium nanowires through a solid-solution-solid transformation mechanism,\textsuperscript{73} where selenium nanocrystals were sonochemically nucleated in a trigonal structure and acted as the seeds of nanowires. Other nonmetal nanomaterials, such as graphene quantum dots, black phosphorus quantum dots and carbon nanodots, can be also prepared from the sonication of the corresponding precursors. When ultrasound was used to irradiate a p-xylene solution containing silica powder and ferrocene, p-xylene would be pyrolyzed to carbon atoms or moieties by the catalytic Fe clusters sonochemically decomposed from the ferrocene and finally produce high-purity, single-walled or multi-walled carbon nanotubes on the nucleation sites provided by silica powder.\textsuperscript{74,75} Lately, Zhou \textit{et al.} fabricated nitrogen-doped carbon quantum dots with temperature-dependent fluorescence by ultrasonic treatment of dopamine in dimethylformamide; moreover, the fluorescence had a sensitive quenching phenomenon towards Fe\textsuperscript{2+} ions.\textsuperscript{76}

5. Secondary sonosynthesis

Apart from primary sonosynthesis, secondary sonosynthesis significantly or more assists in the synthesis of inorganic...
materials as well, because its synthesis mechanism is mainly on the basis that the sonolysis of solvent vapor is capable of producing some active reactants without additional reducing agents, for example, H and OH radicals for water, R radicals for volatile organic vapor, and so on. These radicals are able to act as reactants for some redox chemistry in the production of nanostructured materials. Similar to the volatile organometallic compounds, a few nonvolatile metal precursors dissolved in

| Precursor   | Product                              | Experimental parameters under ultrasound                                                                 | Ref. |
|-------------|--------------------------------------|-----------------------------------------------------------------------------------------------------------|------|
| HAuCl₄      | Au nanoparticles                     | Aqueous solution (70 mL or 200 mL), 1-propanol, argon atmosphere, 0.1 ± 0.01 W mL⁻¹, 20–1062 kHz, 21 ± 2 °C | 78   |
| HAuCl₄      | Au nanorods and nanoparticles        | Aqueous solution (60 mL), CTAB, AgNO₃, ascorbic acid, pH 3.5, argon atmosphere, 200 kHz, 200 W, 27 °C       | 79   |
| HAuCl₄      | Au nanodecahedra                     | PVP/DMF solution (15 mL), NaBH₄, platinum nanoparticles (2–3 nm), 20 kHz, 60 W, 100 °C                  | 80   |
| HAuCl₄      | Au nanobelts                         | Aqueous solution, α-α-glucose (or β-cyclodextrin), 40 kHz, 100 W, sonication for 10–60 min             | 81   |
| AgNO₃, HAuCl₄| Ag nanoplates, Au nanorings           | PVP, DMF solution (40 mL), ambient conditions, 20 kHz, 60 W cm⁻², sonication for 0.5 h                 | 82   |
| HAuCl₄      | Au nanocones                         | 2-Ethoxyaniline, hexane, aqueous solution, 35 kHz, 144 W, 45 °C, sonication for 90 min                 | 83   |
| NaAuCl₄, PdCl₂| Core–shell Au/Pd bimetallic nanoparticles | Aqueous solution (60 mL), sodium dodecyl sulfate, 200 kHz, 200 W, 20 °C                               | 84   |
| HAuCl₄, AgNO₃| Core–shell Au–Ag bimetallic nanoparticles | Aqueous solution (70 mL), polyethylene glycol, ethylene glycol, pH 3.5, argon atmosphere, 20 kHz, 23–47 W cm⁻², room temperature, sonication for 30 min | 85   |
| H₂PtCl₆, HAuCl₄ | Au–Pt bimetallic nanoparticles       | Aqueous solution (6.0 mL), ascorbic acid solution (6.0 mL), sonication for 15 min                        | 86   |
| PtBr₄, CuBr₂ | PtCu₃ bimetallic nanoparticles       | Tetrahydrofuran (200 mL), 2-propanol (20 mL), lithium metal cuttings, naphthalene, 20 kHz, 15 W cm⁻², 20 °C, sonication for 90 min | 87   |
| Pd(NO₃)₂, AgNO₃| PdAg nanoparticles                   | Ethylene glycol/water mixture (60 mL), vulcan carbon XC-72, N₂ atmosphere, 20 kHz, sonication for 3 h (20 s/20 s, on/off) | 88   |
| Pd(acac)₂, Ni(acac)₂, Co(acac)₂, Fe(acac)₃, Mn(acac)₂| PdNi, PdCo, PdPe, PdMn nanoparticles | Ethylene glycol (30 mL), pure Ar, 20 kHz, 150 W, room temperature, sonication for 3 h                      | 89   |
| AuCl₃       | Au nanoclusters                       | Toluene (4 mL), 30 W, 40 kHz, sonication for 0–180 min                                               | 90   |
| AgNO₃       | Ag nanoclusters                       | PMMA solutions (30 mL), pH 4.5, Ar flow, 20 kHz, 25 W cm⁻², sonication for 10–180 min               | 91   |
| AgNO₃       | Ag nanoclusters                       | Aqueous solution (10 mL), BSA, pH 12, 50 W cm⁻², 15 °C, sonication for 4 h (7 : 3, ultrasonic time/ intermittent time) | 92   |
| AgNO₃       | Ag nanoclusters                       | Aqueous solution (25 mL), glutathione, pH 5.0, 40 kHz, 60 W, sonication for 0–170 s                     | 93   |
| Cu(NO₃)₂     | Cu nanoclusters                       | Reduced glutathione, Cu(NO₃)₂, deionized water (5 mL), pH 6.0, sonication for 15 min                  | 94   |
a volatile solvent can be used to prepare nanostructured metals through ultrasound irradiation, whereas the generated nanomaterials are usually crystalized well and are not so amorphous as the nanoparticles form volatile precursors. Table 2 summarizes the secondary sonosynthesis of nanostructured metals from the nonvolatile precursors.

For the production of nanostructured noble metals, the sonochemical reduction provides an alternative to traditional approaches such as photochemical reduction, controlled chemical reduction, radiolytic reduction, and solvothermal synthesis. A systematic study on the sonochemical synthesis of spherical Au nanoparticles referred to the finding published by Grieser and co-workers when HAuCl₄ aqueous solution was sonicated in the presence of alcohols or other similar organic additives, Au nanospheres would be formed with Au(III) being reduced to Au(0), and the particle size was not only largely determined by the solvent/surfactant properties but also related to ultrasound frequency. From the point of view of morphology, nonspherical Au nanoparticles have been also prepared by sonochemical reduction. Au(III) could form Au(0) nanorods in the presence of cetyltrimethylammonium bromide and AgNO₃, and alternatively, it would lead to the formation of monodispersed Au(0) nano-decahedra when poly(vinylpyrrolidone) (PVP) is used as a stabilizing polymer. Similarly, Au nanobelts, Au nanocones, Ag nanoplates, Ag nanowires, Ag nanorings, and even bimetallic nanoparticles with a core–shell structure (e.g., Au/Ag, Au/Pt, Au/Pd, and Pt/Ru) have been produced as well by an ultrasound-assisted Ostwald ripening process. Significantly, high-intensity ultrasound irradiation was able to extremely create small Au nanoclusters, and Cu nanoclusters (less than 2 nm) by using some polymer molecules (e.g., poly(methylacrylic acid) as a capping agent, and such nanoclusters were likely to develop widespread applications in bioimaging, biosensing, and single-molecule studies.

Sonochemical reduction is not limited to the synthesis of nanostructured noble metals, and various metal oxides, metal hydroxides, metal chalcogenides as well as other metal compounds have been also prepared through the treatment of relevant precursors in an analogous manner. For the metal compounds, a typical synthesis way involves the sonication of a solution containing metal salts in the presence of different nonmetal sources, such as air for oxygen, thiourea for sulphur, selenourea for selenium, or others. Kipcak et al. carried out sonochemistry-assisted synthesis of magnesium borate where magnesium chloride hexahydrate and different boron sources (borax, tincalconite, boric acid, and boron oxide) were used as the precursor materials. The synthesis yields were higher than 80%, and the outcomes were MgO(B₂O₃)₃·7H₂O with high crystallinity as per XRD analyses. Pinkas et al. obtained insoluble amorphous uranium phosphates from UO₂ precursors in high-boiling trialkyl phosphate solutions by sonication. Sonolysis experiments were carried out in a frequency of 20 kHz and a power of 0.49 W cm⁻³ under an argon flow at 40 °C, in which trialkyl phosphates served as a phosphate source creating phosphate species by the decomposition of ester molecules and then reacted with uranium precursors. The efficiency of uranium removal from the solution by sonochemical precipitation was higher than 30%, and the obtained amorphous uranium precipitates could change into crystalline uranium diphosphate (UP₂O₇) when heated to 1000 °C. Hence, for the uranium-containing waste streams, sonication might potentially serve as a remote separation for uranium. As an effective light-absorbing material for thin film solar cells, Cu(InₓGa₁₋ₓ)Se₂ showed high conversion efficiency, but the traditional synthesis of Cu(In₁₋ₓGaₓ)₄Se₂ compounds involved typically some toxic organic solvents such as hydrazine, ethylenediamine, and polyethylenimine, as well as a high reaction temperature. Recently, Park et al. designed a substantially greener procedure to yield Cu(In₀.₇Ga₀.₃)Se₂ nanoparticles using a slightly modified sonochemical method, where the reaction was carried out at room temperature with ethanol as the only solvent, NaBH₄ as a reducing agent, and 5 hour ultrasound irradiation. The proposed reaction scheme revealed the role of ultrasound irradiation in decomposing the intermediate Cu₂Se in the reaction pathways, so the sonification time was investigated to form the Cu(InₓGa₁₋ₓ)₄Se₂ compounds with the expected crystalline structure. The short-period sonification irradiation was not enough to form the expected crystal structure, and even the signs of Cu₂Se also appeared. Prolonging the sonification time resulted in much better crystallinity, where 5 hour ultrasound irradiation would yield single-phase tetragonal Cu(InₓGa₀.₃)₁₋ₓSe₂ nanocrystals without any Cu₂Se crystals.

Additionally, secondary sonosynthesis provides a feasible, facial and short-time approach for the synthesis of hybrid inorganic materials. By sonicating sodium chloride, silver nitrate and poly(vinyl pyrrolidone) in ethylene glycol, Ag/AgCl nanocubes with a 115 nm edge length have been produced with silver nanoparticles embedded into AgCl cubic matrices. In the formation of hierarchically structured ZnO/CdS microspheres, CdS nanoparticles were produced by the sonication of a cadmium chloride and aqueous thiourea solution accompanied by the hydrothermal formation of ZnO microspheres. Chen et al. designed a straightforward approach to synthesize Cd(OH)₂/Ag nanorods with a core/satellite structure on the basis of the sonochemical method. Cadmium chloride would form Cd(OH)₂ nanorods via a single sonochemical reaction in a base medium (Fig. 8), followed by the thermal annealing process to obtain highly crystalline CdO nanorods; In the presence of AgNO₃ and ammonia, the prepared CdO nanorods would undergo a second ultrasonication to obtain a core/satellite complex. This proposal was feasible, and the Cd(OH)₂/Ag core/satellite nanorods were prepared successfully, where the deposition of Ag nanodots was completed on the surface when the cubic CdO transformed into monoclinic crystalline Cd(OH)₂. Moreover for the direct surface functionalization of Cd(OH)₂ nanorods with Ag nanodots, the microjets, shock waves and turbulent flows generating the cavitation collapse were found to play a crucial role.

The assistance of other technologies can improve the performance of secondary sonosynthesis in materials preparation. In order to decrease the sintering temperature to prepare strontium hexaferrite nanoparticles, Jesús and Miró reported the synthesis of strontium hexagonal ferrite (SrFe₁₂O₁₉) by...
sonochemistry and annealing. In the synthesis, the sonochemical process yielded an amorphous phase containing Fe$^{3+}$, Fe$^{2+}$, and Sr$^{2+}$ ions from a complexed polyol solution of metallic acetates and diethylene glycol, where Fe$^{2+}$ was partially oxidized to Fe$^{3+}$ due to the formation of H$_2$O$_2$. Subsequently, annealing of the amorphous phase was carried out at temperatures from 300 to 900 °C, providing the intermediate maghemite (γ-Fe$_2$O$_3$) at 300 °C, the phase conversion of maghemite to hematite (α-Fe$_2$O$_3$) at 500 °C, and the generation of final SrFe$_{12}$O$_{19}$ at 800 °C.

High sonication output power and long sonication time (up to 3 h) promoted the crystallinity of amorphous phases, decrease in crystal size, and modification of the morphology of particles. Furthermore, the obtained SrFe$_{12}$O$_{19}$ showed a magnetization of >60 emu g$^{-1}$ consistent with pure hexaferrite obtained by other methods. Similarly, Cavalcante et al. synthesized tungstate (CuWO$_4$) crystals with a triclinic structure based on the sonochemical method and the following heating treatment in a conventional furnace. Copper tungstate hydrate precipitated by the sonochemical reaction would remove the partial water molecules in its lattice as treated at a low temperature from 100 °C to 200 °C, and copper tungstate dihydrate (CuWO$_4$·2H$_2$O) would appear at 300 °C, until the crystals were completely occupied by a single CuWO$_4$ triclinic structure at above 400 °C (Fig. 9). Recently, the simultaneous action of ultrasound and hydrothermal treatment, namely sonohydrothermal treatment, has been developed to accelerate crystallization and improve the catalytic performance of nanocrystalline metal oxides. For the first time, Nikitenko et al. reported the sonohydrothermal synthesis of nanostructured (Ce,Zr)O$_2$ mixed oxides, and the obtained nanocrystal had a higher external mesoporous surface area than that prepared by ultrasonically assisted coprecipitation followed by hydrothermal treatment. Later, they synthesized stable Ti@TiO$_2$ nanoparticles with a core–shell structure by the sonohydrothermal treatment on air-passivated titanium metal nanoparticles in pure water, in which quasi-spherical Ti particles (20–80 nm) were coated by defect-free anatase crystals (5–15 nm) with small amounts of rutile crystals.

Uzunov et al. utilized three synthesis methods (i.e., precipitation; mechanochemical treatment and sonochemistry) to prepare nano-sized zinc oxides from different zinc sources, and the as-synthesized samples had various morphologies with a crystallite size below 20 nm. Under UV irradiation, the sonochemistry-assisted ZnO nanorods exhibited the highest photocatalytic activity for the degradation of malachite green while the precipitation-assisted polycrystalline zinc oxide had a better photocatalytic efficiency under visible irradiation, and on the contrary, the mechanochemistry-assisted nano-sized ZnO led to the deterioration of photocatalytic activity due to inhomogeneous distribution in particle size. In a report of
Ashiri et al., 107 both the sonochemical processing and the mechanochemical approach were considered for the synthesis of BaTiO3 nanopowders. The contrasting results demonstrated that the sonochemical synthesis could obtain highly pure tetragonal BaTiO3 at a much lower processing temperature and shorter time span because the reactant ions would homogeneously order into the perovskite structure in sonication when dissolved in the solution mixture. If there is a proper structure directing agent or template in sonication, more different nanostructured materials can be obtained. Under ammonia conditions, CdCl2 and NaSeSO3 were sonochemically reacted to form hollow CdSe spheres, 108 where Cd(OH)2 from the hydrolysis acted as an in situ template. To make ZnO nanorods and nanoflakes, vertically aligned nanostructures could be deposited on the substrates such as Zn sheets, Si wafers and glass by sonicating a zinc salt when hexamethylenetetramine was used as a shape directing agent. 109 In the presence of soft templates, ultrasound can result in the formation of unique morphologies during the synthesis of nanostructured metal oxides. For example, sonicating the Pb(CH3COO)2, NaWO4 and P123 (a pluronic block copolymer) mixed solution could prepare hollow PbWO4 spindles while only solid particles were obtained in the absence of ultrasound, 110 and the probable reason was that ultrasound changed the P123 micelles into hollow micelle aggregates forming a hollow spindle structure.

6. Synergetic sonosynthesis

The synthesis of many materials does not isolate primary sonosynthesis or secondary sonosynthesis, or it goes through the synergy of serial sonosynthesis. Moreover, some physical or mechanical effects from ultrasound irradiation, such as high-speed microjets, intense shock waves, and interparticle collisions, have been frequently applied in preparing emulsions, agglomerating malleable materials, modifying solid surfaces, exfoliating layered materials, and breaking down friable materials, and they also belong to important factors in the formation of nanostructured materials as well as the enhanced mass transfer and the bulk thermal heating. For instance, ultrasonic spray pyrolysis (USP), sonocrystallization, sonofragmentation as well as other technologies on account of the physical or mechanical effects originating from ultrasound have been utilized to make nanostructured materials. Fig. 10 shows that

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Fig. 9  (I) Schematic representation of the growth mechanism of CuWO4·2H2O and CuWO4 crystals obtained by the sonochemistry method: (a) reaction between complex ions; (b) appearance of the first CuWO4·2H2O nuclei; (c) rotation and alignment of nanocrystals, sharing common crystallographic planes; (d) self-assembly process; (e) aggregation of petal-like crystals; (f) formation of flower-like CuWO4·2H2O microcrystals; (g) crystal growth via heat treatment; (h) irregular stone-like CuWO4·2H2O microcrystals; (i) stone-like CuWO4·2H2O microcrystals and flake-like CuWO4 nanocrystals; (j) formation of aggregated CuWO4 nanocrystals; (k) crystal growth of flake-like CuWO4 nanocrystals. (II) FE-SEM images of CuWO4 crystals heat treated at different temperatures: (a) 100 °C, (b) 200 °C, (c) 300 °C, (d) 400 °C and (e) 500 °C for 1 h, respectively. Reproduced with permission. Copyright 2017 Elsevier.
USP creates some nano- and micromaterials.\textsuperscript{111-113} As a result, the physical or mechanical effects and the sonochemical effects can play a combined part in many synthesis processes as well, and the notable examples will be described in the latter section.

Ultrasound irradiation has become a broadly useful tool to prepare single and few layered materials by overcoming the attractive forces between individual layers to break 3D layer structures down to 2D planar structures. Hammer’s method, as a typical synthesis route to graphene oxide (GO), is often used to oxidize pristine graphite to form graphite oxide, where an increased interlayer distance can consequently weaken the van der Waals force relative to graphite and then produce single or few layered GO by a bath or horn sonication (Table 3).\textsuperscript{115-130} The direct exfoliation of graphite by sonication in a suitable solvent (e.g. N-methyl-pyrrolidone) is a more straightforward method for the formation of single and few layered graphene, in which the surface energy between the solvent and graphite had to match (about 40 mJ m\textsuperscript{-2}) to obtain high-yield exfoliated graphene.\textsuperscript{111} Other layered materials such as MoSe\textsubscript{2}, MoS\textsubscript{2}, WS\textsubscript{2} and Bi\textsubscript{2}Te\textsubscript{3} can also be used to prepare single-layered nanosheets by direct liquid-phase exfoliation under sonication.\textsuperscript{132} In some studies, the physical or mechanical effects of ultrasound dramatically enhance the intercalation of guest substances into layered materials along with the sonochemical synthesis. H\textsubscript{2}PtCl\textsubscript{6} exposure to an H\textsubscript{2} gas stream could be ultrasonically applied in graphite layers to prepare Pt-intercalated graphite.\textsuperscript{133} K-Intercalated compounds (KC\textsubscript{8}) also could be prepared by sonicating graphite with potassium in toluene,\textsuperscript{134} whereas ultrasonication of potassium-intercalated graphite would generate carbon nanoscrolls in ethanol.\textsuperscript{135} So far, the detailed reason has been not fully understood. In addition, a few efforts have been paid to deposit the sonochemically produced...
nanoparticles onto the graphene substrate with a high surface area. Guo et al. prepared the TiO2 nanoparticles deposited on graphene sheets by ultrasonically irradiating GO and TiCl4 in ethanol.136 Au and Fe3O4 nanoparticles also could be used to couple the GO or the graphene.137,138

In addition, ultrasound is a popular method to synthesize other carbon nanomaterials. In traditional carbon nanotube synthesis, sonochemical effects are frequently used to disperse individual single-walled carbon nanotubes in the solution such as N-methyl pyrrrolidone.139 In the cases that volatile organometallic precursors were sonicated to form different structured materials as described above,74–75 p-xylene acting as a carbon source in the presence of low-concentration ferrocene could produce single-walled carbon nanotubes on the silica powder under ultrasound irradiation. Recently, Ha and Jeong have reported a similar sonochemical method to prepare multi-walled carbon nanotubes, which required a higher amount of ferrocene and a little water added to the reactant suspension.140 Carbon nanodots with an average diameter of 2–9 nm were made from the sonication of poly(ethylene glycol)-400 (PEG-400) as a carbon source in a water/silicone oil bath141,142 and when excited at a 390 nm excitation wavelength, the product had 474 nm emission wavelength and 774 A.U. fluorescence intensity. Based on this, Gedanken et al. fabricated an antibacterial material, Ga-doped C-dots on Ga nanoparticles (Ga@C-dots@Ga NPs), where a one-step sonochemical process was applied for the simultaneous fabrication and coating of Ga@C-dots@Ga NPs using PEG-400 and molten gallium (Fig. 11).143 At present, carbon nanodots have been also sonochemically prepared by using other carbon sources like polyacrylic acid, glucose and citric acid.

The combined effects of sonochemical and physical or mechanical processes can promote the preparation of porous materials as an alternative in some cases. Jung and co-workers used 1-methyl-2-pyrrrolidone as a solvent to prepare MOF-177 (MOF or metal–organic framework) or Zn4O(BTB)2 (ZnO or bimodal分布 would be caused as an evidence of Ostwald ripening when the nanoparticles were subjected to sonication. Through the sonosynthesis techniques, Kim et al. developed a rapid and facile method for the in situ growth of MOF films over a metal substrate,155 in which high-intensity ultrasound enhanced the reactivity between metal

### Table 3 Sonocatalysis synthesis or exfoliation of graphene derivatives

| Product | Ultrasound | Ref. |
|---------|------------|------|
| Graphene nanoribbons | 1500 W, 20 kHz | 115 |
| Graphene nanosheets | 500 W | 116 |
| Graphene nanosheets | 20 kHz, 750 W | 117 |
| Graphene nanosheets | — | 118 |
| Graphene dispersions | 51–52 W | 119 |
| Graphene oxide | 600 W | 120 |
| Graphene oxide | 40 kHz, 157 W | 121 |
| Graphite oxide | 360 W | 122 |
| Graphene oxide nanosheets | — | 123 |
| Reduced graphene oxide | 20 kHz, 400 W | 124 |
| Reduced graphene oxide | — | 125 |
| Reduced graphene oxide nanodispersion | 20 kHz, 1000 W or 750 W (ultrasound horn); 130–35 kHz, 200 W (ultrasonic bath) | 126 |
| Sulfonated graphene | 40 W | 127 |
| Sulfonated reduced | 37 kHz | 128 |
| graphene oxide | — | 129 |
| Isoyanate-treated graphene oxide nanoplatelets | 150 W | 130 |
| Chitosan-modified nanoscale graphene oxide | >360 W | 131 |
ion sources and organic ligands after the metal substrate was first treated oxidatively to produce the corresponding metal hydroxide. On the Cu or Zn metal substrates, researchers used such an approach to successfully fabricate four MOF films including Cu-BDC film, Cu-BTC film, ZIF-8 film and MOF-5 film, and found that the crystal size in the films increased with the sonication time except for the MOF-5 film (Fig. 12). On the contrary, MOF-5 had a decrease in the crystallization and growth rate when exposed to long-period ultrasound irradiation, which was likely because the complex formation of several nuclei led to a decrease in crystal size.

Furthermore, the combined effects of ultrasound can also participate in the sonochemical synthesis and/or modification via other approaches, e.g., ultrasound can be applied in promoting the diffusion of dopants into the nanostructured materials. In the study of Xiong et al., high-intensity ultrasound was used to prepare photoluminescence-tunable Mg\textsuperscript{2+} doped ZnO nanoparticles with no MgO phase existing in the ZnO nanoparticles\textsuperscript{154}. In the study of Belova et al., ultrasound irradiation was used to make a slurry containing Au colloids and TiO\textsubscript{2} particles to produce an Au nanoparticle-intercalated mesoporous TiO\textsubscript{2} structure which had enhanced photocatalytic properties\textsuperscript{155}. Recently, Wickleder et al. described a novel ionic liquid-assisted synthesis strategy to produce Eu\textsuperscript{3+}-doped BaFCl nanoparticles by applying sonochemical approaches\textsuperscript{156}, where 1-butyl-3-methylimidazolium tetrafluoroborate (BmimBF\textsubscript{4}) was used as the fluoride source with EuBr\textsubscript{2} or EuSO\textsubscript{4} as the europium source. Eu\textsuperscript{3+}-doped BaFCl nanoparticles were stably suspended in BminBF\textsubscript{4} presenting a relatively narrow size distribution between 20 and 90 nm, where 80\% of the particles were smaller than 40 nm (Fig. 13I). Under daylight, the suspensions with undoped and doped barium fluoride chloride nanoparticles were both colorless because a high reflectance value (above 97\%) in the visible range caused nearly no efficient absorbance. The reflectance decreases in the UV spectral range, allowing the undoped BaFCl particles to display weak dark blue emission probably originating from the C-dot present in the ionic liquid while Eu\textsuperscript{3+}-doped BaFCl particles emitted efficient bluish white light (Fig. 13II). By such a combination of ionic liquid and sonication, Eu\textsuperscript{3+}-doped lanthanide nanophosphates were also fabricated from Ln(NO\textsubscript{3})\textsubscript{3}·6H\textsubscript{2}O and 1-hexyl-3-methylimidazolium dihydric phosphate. Nagabhushana et al. reported the synthesis of Eu\textsuperscript{3+}-doped Y\textsubscript{2}O\textsubscript{3} nanophosphors by a modified sonochemical method using aloe vera gel as a surfactant\textsuperscript{157} and investigated the effect of sonication time on the morphology of nanophosphors. Within a short sonication time, the nanophosphors showed agglomerated microstructures, and with the sonication time increasing, the size slightly
reduced and began to be uniformly spherical until a prolonged sonication time of over 6 hours caused agglomerated microstructures again because uniform spherical structures were thriving themselves. Previous to Wickleder et al. and Nagabhushana et al., Xu and co-workers had successfully synthesized hexagonal and tetragonal LnPO₄:Eu³⁺ nanostructures (Ln = La, Gd, and Y) through a simple and facile ionic liquid-assisted sonochemical method,¹⁵⁸ where the rapid reaction rate was attributed to the acceleration effect of ionic liquid combined with ultrasound irritation. The obtained LnPO₄:Eu³⁺ displayed four different types of morphologies including nanowires, nanorods, nanowire bundles and nanoparticles, which might be relevant to the period of the sonication process.

In addition, what is more, the microjets and shock waves originating from the ultrasound near the solid materials can induce a few physical changes on the surface of particles or

Fig. 12 (I) Schematic illustration of the two-step method for the fabrication of different thin MOF films. (II) SEM images of Cu-BTC with 0.5 mM BTC under ultrasonic irradiation for (a) 5 min, (b) 15 min, (c) 30 min, and (d) 60 min; SEM images of Cu-BDC with 1 mM BDC under ultrasonic irradiation for (e) 5 min, (f) 15 min, (g) 30 min, and (h) 60 min. (III) SEM images of ZIF-8 with 0.1 mM 2-MIM under ultrasonic irradiation for (a) 5 min, (b) 15 min, (c) 30 min, and (d) 60 min. SEM images of MOF-5 with 1 mM BDC under ultrasonic irradiation for (e) 5 min, (f) 15 min, (g) 30 min, and (h) 60 min. Reproduced with permission.¹⁵³ Copyright 2018 Elsevier.
substrates. For instance, the anticorrosion surface coatings can be improved via the treatment of high-intensity ultrasound in which a newly active oxide layer will form with the existing oxide layer being removed. Ultrasound irradiation can also improve the sol–gel preparation of nanostructured metal oxides by accelerating the hydrolysis process, improving the phase purity, and creating the metal oxides with narrower size distribution and higher surface area. In a study of Yu et al., TiO₂ nanoparticles produced by the ultrasound irradiation of the precursor solution had a higher photocatalytic activity, which was attributed to the accelerated hydrolysis in sonication improving the crystallinity of TiO₂. To obtain thin zirconium dioxide layers on structured reactors, Jodłowski developed an efficient ultrasound-assisted sol–gel method through the synergistic combination of three processes including the sonochemical synthesis of Zr sol–gel from a Zr(IV) n-propoxide precursor solution, the addition of ethylene glycol and glycerol as stabilizing agents, and the deposition of ZrO₂ on FeCr alloy supports using the dip-coating method. The results displayed that the ZrO₂ films on the metallic structure were dense and uniform without any impurities. In the study of Sierra-Salazar et al., the hierarchically porous Pt/SiO₂ catalyst was prepared in aqueous medium via the combination of latex synthesis, sonochemical reduction and a two-step catalysed sol–gel process, and its mesopore and macropore size ranged as large as 2–15 nm and 90–400 nm, respectively. For such a silica-supported Pt catalyst, the noble metal Pt distribution could be enhanced at low loadings by controlling the hierarchical porosity of the support material. Manoharan et al. tailored a hybrid method of the precipitation technique and ultrasonication to accomplish the preparation of polycrystalline zirconia nanophosphors from a zirconium oxalate precursor complex. As a physical aid to the synthesis process, the acoustic wave well controlled the grain size of nano-zirconia where the particles had a uniform spherical shape and narrow size distribution in the range of 15–25 nm, and the crystal structure was found to be predominantly tetragonal at room temperature. By the sonochemical coprecipitation, Zhang et al. prepared catalase-inorganic hybrid microflowers (Cat-HMFs) by using catalase as an organic component and copper phosphate (Cu₃(PO₄)₂) as an inorganic component. Then, Cat-HMFs were dropped onto the glassy carbon electrode to fabricate a H₂O₂ biosensor. Amperometric detection results indicated that such a biosensor displayed excellent current response stability, selectivity and long-term storage stability toward H₂O₂ detection.

Certainly, the inorganic-based hybrid nanomaterials such as inorganic/polymer composites and inorganic/biomolecule composites or other multi-level composites have been produced largely based on combined sonosynthesis. For instance, Ashokkumar et al. carried out the sonochemical formation of polystyrene/SiO₂ Janus particles on the basis of the
phase separation mechanism between the tetraethoxysilane and growing polystyrene particles.\textsuperscript{165} In our studies, the magnetic nanoparticles were either fixed on the surface of carrier supporters as a shell or loaded into the interior of carrier supporters as a core (Fig. 14).\textsuperscript{166} We have been also reviewed the sonochemical fabrication of inorganic/biomolecule composites for drug delivery and described the multiformity and multifunctionality of products according to the synthetic materials, implementation schemes, or specific demands. In fact, the structure, size, stability and activity of inorganic-based hybrid nanomaterials are important to both the quality of properties and the acceptability of applications, and the relevant research results or viewpoints have been reviewed in detail in other papers.\textsuperscript{167–173}

7. Future outlook

Ultrasound-aided materials synthesis has been developed rapidly and remarkably in the last few decades, constantly in a few novel ways to simplify the synthesis processes or to enhance the properties of products. Indeed, ultrasound irradiation shows potential to assemble nano-structured inorganic materials of defined sizes and with pre-defined functionalities, or together with the recent advances or methods for purpose-specific or site-specific modification, significantly expands its applications in materials synthesis. Thereby, nano-structured inorganic materials in association with sonochemical synthesis are an available future direction. Even so, many challenges and anticipations are still online for the in-depth development of either sonosynthesis or the resultant products. The probable challenges could be as follows: more mechanistic and experimental understanding of the cavitation phenomenon on the nano- and micro-levels is needed to settle a matter in controlling the sonosynthesis processes; the difference of raw materials or a variety of microdevices asks for more designs of ultrasound-based synthesis platforms; sometimes for the ultrasound-assisted preparation of nanostructured materials, controlled morphologies, structures, and compositions are essential but a lot unsolved; the performance, durability, selectivity as well as low cost of product materials are still highly demanding; besides a high mechanical stability and a long shelf life, all the products had to accurately act according to on-site conditions or stimulus; finally, sonosynthesis is an energy consuming process in materials preparation, and although the production of ultrasound from electrical power can be extremely efficient, sonochemistry remains energy inefficient since the coupling of ultrasound into chemically useful cavitation events has low yield, so more effective ways to induce more cavitation in liquids may alleviate the current limitation. Certainly, there are more known and unknown areas meriting

Fig. 14 TEM images of organic/BSA composites with a magnetic shell (A) and with a magnetic core (B); SEM images of organic/BSA composites with a magnetic shell (C) and with a magnetic core (D), where the close-up images lay in the inset of panel (C) and (D). Reproduced with permission.\textsuperscript{166} Copyright 2019 Elsevier.
further study on ultrasound or sonochemical synthesis, such as the interaction mechanism between the materials at the cavitation interface, the controlled energy distribution of collapsing bubbles, the heterogeneous nucleation onto the solid surfaces with different properties, the in situ observation of the product’s macroscopic structures in the formation, and so on.

8. Conclusion

Ultrasound is appealing and conducive to the preparation or modification of nanomaterials. This review simply gives the view on the chemical, physical and mechanical effects from ultrasound irradiation, presenting the basic principles or mechanisms of primary sonosynthesis and secondary sono-synthesis. Meanwhile, it describes the preparation of inorganic materials from the perspective of sonosynthesis, highly focusing on different inorganics including metals, alloys, metal compounds (e.g., metal oxides, metal sulfides, and metal nitrides), non-metals (e.g., carbon materials, silicon materials, and selenium materials) and hybrid composites, and widely covering a variety of structures such as solid structures, hollow structures, core–shell structures, porous structures, nanotube structures, nanorod structures, and layered structures. In addition, the review also provides the probable challenges and technological potential for the future advancements on the sonochemical synthesis applications. We hope that such a review can provide a comprehensive understanding of sonochemistry as well as the synthesis mechanism and broaden the updated applications in catalysis or other fields.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

1 G. Chatel, How sonochemistry contributes to green chemistry?, Ultrason. Sonochem., 2018, 40, 117–122.
2 T. J. Mason, Industrial, sonochemistry: potential and practicality, Ultrasonics, 1992, 30, 192–196.
3 N. Pokhrel, P. K. Vabbina and N. Pala, Sonochemistry: science and engineering, Ultrason. Sonochem., 2016, 29, 104–128.
4 Z. Li, T. Zhuang, J. Dong, L. Wang, J. Xia, H. Wang, X. Cui and Z. Wang, Sonochemical fabrication of inorganic nanoparticles for applications in catalysis, Ultrason. Sonochem., 2021, 71, 105384.
5 K. Hanajiri, T. Maruyama, Y. Kaneko, H. Mitsui, S. Watanabe, M. Sata, R. Nagai, T. Kashima, J. Shibahara, M. Omata and Y. Matsumoto, Microbubble-induced increase in ablation of liver tumors by high-intensity focused ultrasound, Hepatol. Res., 2006, 36, 308–314.
6 S. L. Polliachik, W. L. Chandler, P. D. Mourad, R. J. Ollos and L. A. Crum, Activation, aggregation and adhesion of platelets exposed to high-intensity focused ultrasound, Ultrasound in Medicine and Biology, 2001, 27, 1567–1576.
7 Y. S. Tung, H. L. Liu, C. C. Wu, K. C. Ju, W. S. Chen and W. L. Lin, Contrast-agent-enhanced ultrasound thermal ablation, Ultrasound in Medicine and Biology, 2006, 32, 1103–1110.
8 M. A. Almessiere, A. V. Trukhanov, F. A. Khan, Y. Slimani, N. Tashkandi, V. A. Turchenko, T. I. Zubar, D. I. Tishkevich, S. V. Trukhanov, L. V. Panina and A. Baykal, Correlation between microstructure parameters and anti-cancer activity of the $\text{[Mn}_{0.5}\text{Zn}_{0.5}\text{Eu}_{0.5}\text{Nd}_{0.5}\text{Fe}_{2-0.5}]_{2}\text{O}_{3}$ nanoferrites produced by modified sol-gel and ultrasonic methods, Ceram. Int., 2020, 46, 7346–7354.
9 L. Qiu, Y. Jiang, L. Zhang, L. Wang and Y. Luo, Ablation of synovial pannus using microbubble-mediated ultrasonic cavitation in antigen-induced arthritis in rabbits, Rheumatol. Int., 2012, 32, 3813–3821.
10 K. Yamamoto, P. M. King, X. Wu, T. J. Mason and E. M. Joyce, Effect of ultrasonic frequency and power on the disruption of algal cells, Ultrason. Sonochem., 2015, 24, 165–171.
11 M. A. Almessiere, Y. Slimani, A. D. Korkmaz, S. G¨uner, A. Baykal, S. E. Shirsath, I. Erkan and P. Kögerler, Sonochemical synthesis of $\text{Dy}^{3+}$ substituted $\text{Mn}_{0.5}\text{Zn}_{0.5}\text{Fe}_{2}\text{O}_{4}$ nanoparticles: Structural, magnetic and optical characteristics, Ultrason. Sonochem., 2020, 61, 104836.
12 S. Anandan, V. K. Ponnusamy and M. Ashokkumar, A review on hybrid techniques for the degradation of organic pollutants in aqueous environment, Ultrason. Sonochem., 2020, 67, 105130.
13 S. Ye, M. Yan, X. Tan, J. Liang, G. Zeng, H. Wu, B. Song, C. Zhou, Y. Yang and H. Wang, Facile assembled biochar-based nanocomposite with improved graphitization for efficient photocatalytic activity driven by visible light, Appl. Catal., B, 2019, 250, 78–88.
14 M. A. Almessiere, Y. Slimani, A. D. Korkmaz, A. Baykal, H. Albetr, T. A. Saleh, M. Sertkol and I. Erkan, A study on the spectral, microstructural, and magnetic properties of Eu-Nd double-substituted $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{Fe}_{2}\text{O}_{19}$ hexaferrites synthesized by an ultrasonic-assisted approach, Ultrason. Sonochem., 2020, 62, 104847.
15 B. M. Teo, Ultrasonic synthesis of polymer nanoparticles, Handbook of Ultrasonics and Sonochemistry, 2013, pp. 1–29.
16 M. A. Almessiere, Y. Slimani, U. Kurtan, S. Guner, M. Sertkol, S. E. Shirsath, S. Akhtar, A. Baykal and I. Erkan, Structural, magnetic, optical properties and cation distribution of nanosized $\text{Co}_{0.7}\text{Zn}_{0.3}\text{Fe}_{2-0.5}\text{O}_{4}$
(0.0 < x < 0.04) spinel ferrites synthesized by ultrasonic irradiation, *Ultrason. Sonochem.*, 2019, 58, 104638.

17 L. H. Thompson and L. K. Doraiswamy, Sonochemistry: science and engineering, *Ind. Eng. Chem. Res.*, 1999, 38, 1215–1249.

18 M. Bradley, M. Ashokkumar and F. Grieser, Sonochemical production of fluorescent and phosphorescent latex particles, *J. Am. Chem. Soc.*, 2003, 125, 525–529.

19 M. T. Taghizadeh and T. Asadpour, Effect of molecular weight on the ultrasonic degradation of poly(vinyl-pyrrolidone), *Ultrason. Sonochem.*, 2009, 16, 280–286.

20 M. A. Almessiere, Y. Slimani, H. Gungunes, V. G. Kostishyn, S. V. Trukanov, A. V. Trukanov and A. Baykal, Impact of Eu³⁺ ion substitution on structural, magnetic and microwave traits of Ni-Cu-Zn spinel ferrites, *Ceram. Int.*, 2020, 46, 11124–11131.

21 N. K. Morya, P. K. Iyer and V. S. Moholkar, A physical insight into sonochemical emulsion polymerization with cavitation bubble dynamics, *Polymer*, 2008, 49, 1910–1925.

22 J. Gonzalez-Garcia, V. Saez, I. Tudela, M. I. Diez-Garcia, M. D. Esclapez and O. Louisnard, Sonochemical treatment of water polluted by chlorinated organo compounds. A review, *Water*, 2010, 2, 28–74.

23 M. Siddique, R. Farooq, Z. M. Khan, Z. Khan and S. Shaukat, Enhanced decomposition of reactive blue 19 dye in ultrasound assisted electrochemical reactor, *Ultrason. Sonochem.*, 2011, 18, 190–196.

24 B. R. Carvalho and M. A. Pimenta, Resonance Raman spectroscopy in semiconducting transition-metal dichalcogenides: basic properties and perspectives, *2D Mater.*, 2020, 7, 042001.

25 A. P. Kiseleva, G. O. Kiselev, V. O. Nikolaeva, G. Seisenbaeva, V. Kessler, P. V. Krivoshapkin and E. F. Krivoshapkina, Hybrid spider silk with inorganic nanomaterials, *Nanomaterials*, 2020, 10, 1853.

26 E. J. Braham, R. D. Davidson, M. Al-Hashimi and R. Arroyave, Navigating the design space of inorganic materials synthesis using statistical methods and machine learning, *Dalton Trans.*, 2020, 49, 11480–11488.

27 R. Wang, Y. Wei, L. An, R. Yang, L. Guo, Z. Weng, P. Da, W. Chen, J. Jin, J. Li and P. Xi, Construction and application of interfacial inorganic nanostructures, *Chin. J. Chem.*, 2020, 38, 772–786.

28 D. G. Shchukin and H. Moehwald, Sonochemical nanosynthesis at the engineered interface of a cavitation microbubble, *Phys. Chem. Chem. Phys.*, 2006, 8, 3496–3506.

29 A. Cinoco, A. Ribeiro, C. Oliveira, P. Parpot, A. Gomes and A. Cavaco-Paulo, Albumin/asparaginase capsules prepared by ultrasound to retain ammonia, *Appl. Microbiol. Biotechnol.*, 2016, 100, 9499–9508.

30 Z. Li, Z. Wang, X. Du, C. Shi and X. Cui, Sonochemistry-assembled stimuli-responsive polymer microcapsules for drug delivery, *Adv. Healthcare Mater.*, 2018, 7, 1701326.

31 M. Vinatoru and T. J. Mason, Can sonochemistry take place in the absence of cavitation? – a complementary view of how ultrasound can interact with materials, *Ultrason. Sonochem.*, 2019, 52, 2–5.

32 T. Leighton, *The Acoustic Bubble*, Academic press, 2012.

33 K. S. Suslick, The chemical effects of ultrasound, *Sci. Am.*, 1989, 260, 80–86.

34 C. R. Brenner, *Cavitation and Bubble Dynamics*, Oxford University Press, Oxford, 1995.

35 K. S. Suslick, N. C. Eddingssaa, D. J. Flannigan, S. D. Hopkins and H. X. Xu, The chemical history of a bubble, *Acc. Chem. Res.*, 2018, 51, 2169–2178.

36 T. G. McKenzie, F. Karimi, M. Ashokkumar and P. G. G. Qiao, Ultrasound and sonochemistry for radical polymerization: sound synthesis, *Chem.–Eur. J.*, 2019, 25, 5372–5388.

37 D. V. Prasad Naidu, R. Rajan, R. Kumar, K. S. Gandhi, V. H. Arakeri and S. Chandrasekaran, Modeling of a batch sonochemical reactor, *Chem. Eng. Sci.*, 1994, 49, 877–888.

38 M. H. Entezari, P. Kruijs and R. Otson, The effect of frequency on sonochemical reactions. III: dissociation of carbon disulfide, *Ultrason. Sonochem.*, 1997, 4, 49–54.

39 M. A. Margulis, Sonoluminescence and sonochemical reactions in cavitation fields. A review, *Ultrasonics*, 1985, 23, 157–169.

40 A. A. Ndiaye, R. Pflieger, B. Siboulet and S. I. Nikitenko, The origin of isotope effects in sonoluminescence spectra of heavy and light water, *Angew. Chem., Int. Ed.*, 2013, 52, 2478–2481.

41 R. Silva, H. Ferreira, N. G. Azoia, U. Shimanovich, G. Freddi, A. Gedanken and A. C. Paulo, Insights on the mechanism of formation of protein microspheres in a biphasic system, *Mol. Pharmaceutics*, 2012, 9, 3079–3088.

42 R. Ji, R. Pflieger, M. Virot and S. I. Nikitenko, Multibubble sonochemistry and sonoluminescence at 100 kHz: the missing link between low- and high-frequency ultrasound, *J. Phys. Chem. B*, 2018, 122, 6989–6994.

43 N. S. M. Yusof and M. Ashokkumar, Sonochemical synthesis of gold nanoparticles by using high intensity focused ultrasound, *ChemPhysChem*, 2015, 16, 775–781.

44 J. J. Hinman and K. S. Suslick, Nanostructured materials synthesis using ultrasound, *Top. Curr. Chem.*, 2017, 375, 12.

45 K. S. Suslick, Sonochemistry, *Science*, 1990, 247, 1439–1445.

46 J. R. Blake and D. C. Gibson, Cavitation bubbles near boundaries, *Annu. Rev. Fluid. Mech.*, 1987, 19, 99–123.

47 C. D. Ohl, T. Kurz, R. Geisler, O. Lindau and W. Lauterborn, Bubble dynamics, shock waves and sonoluminescence, *Philos. Trans. R. Soc.*, A, 1999, 357, 269.

48 D. G. Shchukin, D. Radziuk and H. Moehwald, Ultrasonic fabrication of metallic nanomaterials and nanoalloys, *Annu. Rev. Mater. Res.*, 2010, 40, 345–362.

49 J. H. Bang and K. S. Suslick, Applications of ultrasound to the synthesis of nanostructured materials, *Adv. Mater.*, 2010, 22, 1039–1059.

50 M. Guo, K. Li, H. Zhang, X. Min, X. Hu, W. Guo, J. Jia and T. Sun, Enhanced catalytic activity of oxygenated VOC deep oxidation on highly active in-situ generated GdMn₂O₅/GdMnO₃ catalysts, *J. Colloid Interface Sci.*, 2020, 578, 229–241.
Synthesis of TiO2-x/W18O49 hollow double-shell and core-shell microspheres for CO2 photoreduction under visible light, *Chem. Commun.*, 2020, 56, 12150–12153.

Z. Wang, H. Yang, R. Liu, S. Xie, Y. Liu, H. Dai, H. Huang and J. Deng, Probing tolune catalytic removal mechanism over supported Pt nano- and single-atom-catalyst, *J. Hazard. Mater.*, 2020, 392, 122558.

Z. Li, L. Qiang, S. Zhong, H. Wang and X. Cui, Synthesis and characterization of monodisperse magnetic Fe3O4@BSA core-shell nanoparticles, *Colloids Surf., A*, 2013, 436, 1145–1151.

K. S. Suslick, S. B. Choe, A. Cichowlas and M. W. Grinstaff, Sonochemical synthesis of amorphous iron, *Nature*, 1991, 353, 414–416.

M. W. Grinstaff, A. A. Cichowlas, S. B. Choe and K. S. Suslick, Effect of cavitation conditions on amorphous metal synthesis, *Ultrasonics*, 1992, 30, 168–172.

T. Hyeon, M. Fang and K. S. Suslick, Nanostructured molybdenum carbide: sonochemical synthesis and catalytic properties, *J. Am. Chem. Soc.*, 1996, 118, 5492–5493.

C. Cau and S. I. Nikitenko, Mechanism of W(CO)6 sonolysis in diphenylmethane, *Ultrason. Sonochem.*, 2012, 19, 498–502.

Y. Koltypin, X. Cao, R. Prozorov, J. Balogh, D. Kaptas and A. Gedanken, Sonochemical synthesis of iron nitride nanoparticles, *J. Mater. Chem.*, 1997, 7, 2453–2456.

P. M. Sakkas, C. Bozes, D. G. Kanellopoulou, G. Sourkouni and C. Argirius, A study on the synchronous decoration of molybdenum oxide or tungsten oxide nanoparticles on anode materials for natural gas fed solid oxide fuel cells using ultrasounds, *Ultrason. Sonochem.*, 2019, 59, 104715.

A. I. Argüelles-Pesqueira, N. M. Diéguez-Armenta, A. K. Bobadilla-Valencia, S. K. Nataraj, A. Rosas-Durazo, R. Esquivel, M. E. Álvarez-Ramos, R. Escudero, A. K. Bobadilla-Valencia, J. B. Wu, X. Y. Ma, Z. H. Liu, Y. Q. Zhang, D. R. Yang, X. H. Huang and J. P. Tu, Porous Co3O4 nanotubes derived from Co6(CO)12 clusters on carbon nanotube templates: a highly efficient material for Li-Battery applications, *Adv. Mater.*, 2007, 19, 4505–4509.

J. H. Bang and K. S. Suslick, Sonochemical synthesis of nanosized hollow hematite, *J. Am. Chem. Soc.*, 2007, 129, 2242–2243.

P. M. Sakkas, C. Bozes, D. G. Kanellopoulou, G. Sourkouni and C. Argirius, A study on the synchronous decoration of molybdenum oxide or tungsten oxide nanoparticles on anode materials for natural gas fed solid oxide fuel cells using ultrasounds, *Ultrason. Sonochem.*, 2019, 59, 104715.
L. M. Liz-Marzán, Synthesis and optical properties of gold nanodecahedra with size control, \textit{Adv. Mater.}, 2006, \textbf{18}, 2529–2534.

J. Zhang, J. Du, B. Han, Z. Liu, T. Jiang and Z. Zhang, Sonochemical formation of single-crystalline gold nanobelts, \textit{Angew. Chem., Int. Ed.}, 2006, \textbf{45}, 1116–1119.

L. P. Jiang, S. Xu, J. M. Zhu, J. R. Zhang, J. J. Zhu and H. Y. Chen, Ultrasonic-assisted synthesis of monodisperse single-crystalline silver nanoplates and gold nanorings, \textit{Inorg. Chem.}, 2004, \textbf{43}, 5877–5883.

P. Zhang, J. He, X. Ma, J. Gong and Z. Nie, Ultrasound assisted interfacial synthesis of gold nanocones, \textit{Chem. Commun.}, 2013, \textbf{49}, 987–989.

Y. Mizukoshi, K. Okitsu, Y. Maeda, T. A. Yamamoto, R. Oshima and Y. Nagata, Sonochemical preparation of bimetallic nanoparticles of gold/palladium in aqueous solution, \textit{J. Phys. Chem. B}, 1997, \textbf{101}, 7033–7037.

S. Anandan, F. Grieser and M. Ashokkumar, Sonochemical synthesis of Au-Ag core-shell bimetallic nanoparticles, \textit{J. Phys. Chem. C}, 2008, \textbf{112}, 15102–15105.

H. Ataee-Esfahani, L. Wang, Y. Nemoto and Y. Yamauchi, Synthesis of bimetallic Au@Pt nanoparticles with Au core and nanostructured Pt shell toward highly active electrocatalysts, \textit{Chem. Mater.}, 2010, \textbf{22}, 6310–6318.

C. Gümeči, D. U. Cearnaigh, D. J. Casadonte and C. Korzeniewski, Synthesis of PtCu₃ bimetallic nanoparticles as oxygen reduction catalysts via a sonochemical method, \textit{J. Mater. Chem. A}, 2013, \textbf{1}, 2322–2329.

A. Godínez-García, J. F. Pérez-Robles, H. V. Martínez-Tejada and O. Solorza-Feria, Characterization and electrocatalytic properties of sonochemical synthesized PdAg nanoparticles, \textit{Mater. Chem. Phys.}, 2012, \textbf{134}, 1013–1019.

M. A. Matin, J. H. Jang and Y. U. Kwon, PdM nanoparticles (M=Ni, Co, Fe, Mn) with high activity and stability in formic acid oxidation synthesized by sonochemical reactions, \textit{J. Power Sources}, 2014, \textbf{262}, 356–363.

J. Li, C. J. Ke, C. Lin, Z. H. Cai, C. Y. Chen and W. H. Chang, Facile method for gold nanocluster synthesis and fluorescence control using toluene and ultrasound, \textit{J. Med. Biol. Eng.}, 2013, \textbf{33}, 23–28.

H. Xu and K. S. Suslick, Sonochemical synthesis of highly fluorescent Ag nanoclusters, \textit{ACS Nano}, 2010, \textbf{4}, 3209–3214.

T. Liu, L. Zhang, H. Song, Z. Wang and Y. Lv, Sonochemical synthesis of Ag nanoclusters: electrogenerated chemiluminescence determination of dopamine, \textit{Luminescence}, 2013, \textbf{28}, 530–535.

T. Zhou, M. Rong, Z. Cai, C. J. Yang and X. Chen, Sonochemical synthesis of highly fluorescent glutathione-stabilized Ag nanoclusters and S²⁻ sensing, \textit{Nanoscale}, 2012, \textbf{4}, 4103–4106.

C. Wang, H. Cheng, Y. Huang, Z. Xu, H. Lin and C. Zhang, Facile sonochemical synthesis of pH-responsive copper nanoclusters for selective and sensitive detection of Pb²⁺ in living cells, \textit{Analyst}, 2015, \textbf{140}, 5634–5639.

M. Yildirim, A. S. Kipcak and E. M. Derun, Sonochemical-assisted magnesium borate synthesis from different boron sources, \textit{Pol. J. Chem. Technol.}, 2017, \textbf{19}, 81–88.

I. Doroshenko, J. Zurkova, Z. Moravec, P. Bezidicka and J. Pinkas, Sonochemical precipitation of amorphous uranium phosphates, from trialkyl phosphate solutions and their thermal conversion to UP₂O₇, \textit{Ultrason. Sonochem.}, 2015, \textbf{26}, 157–162.

T. T. T. Le, T. V. Vu, H. Kim, D. Jeong, B. Pejja, N. T. N. Truong and C. Park, Green and low-cost synthesis of CIGSe nanoparticles using ethanol as a solvent by a sonochemical method-A new approach, \textit{ Mater. Chem. Phys.}, 2018, \textbf{207}, 522–529.

D. Chen, S. H. Yoo, Q. Huang, G. Ali and S. O. Cho, Sonochemical synthesis of Ag/AgCl nanocubes and their efficient visible-light-driven photocatalytic performance, \textit{Chem.–Eur. J.}, 2012, \textbf{18}, 5192–5200.

F. Xu, Y. Yuan, H. Han, D. Wu, Z. Gao and K. Jiang, Synthesis of ZnO/CDSS hierarchical heterostructure with enhanced photocatalytic efficiency under nature sunlight, \textit{CrystEngComm}, 2012, \textbf{14}, 3615–3622.

M. Abbasa, W. Tawfik and J. Chen, CdO nanorods and Cd(OH)₂/Ag core/satellite nanorods: Rapid and efficient sonochemical synthesis, characterization and their magnetic properties, \textit{Ultrason. Sonochem.}, 2018, \textbf{40}, 577–582.

R. L. Palominio, A. M. B. Miró, F. N. Tenorio, F. S. D. Jesús, C. A. C. Escobedo and S. Ammar, Sonochemical assisted synthesis of SrFe₂O₅₉ nanoparticles, \textit{Ultrason. Sonochem.}, 2016, \textbf{29}, 470–475.

R. L. P. Resendiz, F. S. D. Jesús, C. A. C. Escobedo, L. E. H. Cruz and A. M. B. Miró, Effect of sonication output power on the crystal structure and magnetism of SrFe₂O₅₉ nanoparticles, \textit{Crystals}, 2018, \textbf{8}, 45.

E. L. S. Souza, J. C. Szczonoski, I. C. Nogueira, M. A. P. Almeida, M. O. Orlandi, M. S. Li, R. A. S. Luz, M. G. R. Filho, E. Longo and L. S. Cavalcante, Structural evolution, growth mechanism and photoluminescence properties of CuWO₄ nanocrystals, \textit{Ultrason. Sonochem.}, 2017, \textbf{38}, 256–270.

C. Cau, Y. Guari, T. Chave, J. Larionova, P. Pochon and S. I. Nikitenko, Sonohydrothermal synthesis of nanostructured (Ce,Zr)O₂ mixed oxides with enhanced catalytic performance, \textit{J. Phys. Chem. C}, 2013, \textbf{117}, 22827–22833.

S. I. Nikitenko, T. Chave, C. Cau, H. Brau and V. Fland, Photothermal hydrogen production using noble-metal-free Ti@TiO₂ core-shell nanoparticles under visible-NIR light irradiation, \textit{ACS Catal.}, 2015, \textbf{5}, 4790–4795.

M. Gancheva, M. Markova-Velichkova, G. Atanasova, D. Kovacheva, I. Uzunov and R. Cukeva, Design and photocatalytic activity of nanosized zinc oxides, \textit{Appl. Surf. Sci.}, 2016, \textbf{368}, 258–266.

A. Moghtada and R. Ashiri, Superiority of sonochemical processing method for the synthesis of barium titanate nanocrystals in contrast to the mechanochemical approach, \textit{Ultrason. Sonochem.}, 2018, \textbf{41}, 127–133.
108 J. Zhu, S. Xu, H. Wang, J. Zhu and H. Chen, Sonoechemical synthesis of CdSe hollow spherical assemblies via an in situ template route, Adv. Mater., 2003, 15, 156–159.

109 P. K. Vabbina, A. Kaushik, N. Pokhrel, S. Bhansali and N. Pala, Electrochemical cortisol immunosensors based on sonoechemically synthesized zinc oxide 1D nanorods and 2D nanoflakes, Biosens. Bioelectron., 2015, 63, 124–130.

110 J. Geng, J. Zhu, D. Lu and H. Chen, Hollow PbWO₄ nanospindles via a facile sonoechemical route, Inorg. Chem., 2006, 45, 8403–8407.

111 J. M. Rankin, N. K. Neelakantan, K. E. Lundberg, E. M. Grzinic, C. J. Murphy and K. S. Suslick, Magnetic, fluorescent, and copolymeric silicone microspheres, Adv. Sci., 2015, 2, 6.

112 A. K. P. Mann, S. Wicker and S. E. Skrabalak, Aerosol-assisted molten salt synthesis of NaInS₂ nanoplates for use as a new photoanode material, Adv. Mater., 2012, 24, 6186–6191.

113 Y. Zhang, L. A. Huff, A. A. Gewirth and K. S. Suslick, Synthesis of manganese oxide microspheres by ultrasonic spray pyrolysis and their application as supercapacitors, Part. Part. Syst. Charact., 2015, 32, 899–906.

114 K. Muthoosamy and S. Manickam, State of the art and recent advances in the ultrasound-assisted synthesis, exfoliation and functionalization of graphene derivatives, Ultrason. Sonochem., 2017, 39, 478–493.

115 Z. Wu, W. Ren, L. Gao, B. Liu, J. Zhao and H. Cheng, Efficient synthesis of graphene nanoribbons sonochemically cut from graphene sheets, Nano Res., 2010, 3, 16–22.

116 D. Li, M. B. Mueller, S. Gilje, R. B. Kaner and G. G. Wallace, Processable aqueous dispersions of graphene nanosheets, Nat. Nanotechnol., 2007, 3, 101–105.

117 K. Krishnamoorthy, G. Kim and S. J. Kim, Graphene nanosheets: Ultrasound assisted synthesis and characterization, Ultrason. Sonochem., 2013, 20, 644–649.

118 X. Li, G. Zhang, X. Bai, X. Sui, X. Wang, E. Wang and H. Dai, Highly conducting graphene sheets and Langmuir–Blodgett films, Nat. Nanotechnol., 2008, 3, 538–542.

119 A. A. Green and M. C. Hersam, Solution phase production of graphene with controlled thickness via density differentiation, Nano Lett., 2009, 9, 4031–4036.

120 Z. Fan, W. Kai, J. Yan, T. Wei, L. Zhi, J. Feng, Y. Ren, L. Song and F. Wei, Facile synthesis of graphene nanosheets via Fe reduction of exfoliated graphite oxide, ACS Nano, 2011, 5, 191–198.

121 T. Soltani and B. Lee, Low intensity-ultrasonic irradiation for highly efficient, eco-friendly and fast synthesis of graphene oxide, Ultrason. Sonochem., 2017, 38, 693–703.

122 H. Yang, H. Li, J. Zhai, L. Sun and H. Yu, Simple synthesis of graphene oxide using ultrasonic cleaner from expanded graphite, Ind. Eng. Chem. Res., 2014, 53(46), 17878–17883.

123 A. Esmaeili and M. H. Entezari, Facile and fast synthesis of graphene oxide nanosheets via bath ultrasonic irradiation, J. Colloid Interface Sci., 2014, 432, 19–25.

124 A. Abulizi, K. Okitsu and J. Zhu, Ultrasound assisted reduction of graphene oxide to graphene in L-ascorbic acid aqueous solutions: Kinetics and effects of various factors on the rate of graphene formation, Ultrason. Sonochem., 2014, 21, 1174–1181.

125 T. Soltani and B. Lee, A benign ultrasonic route to reduced graphene oxide from pristine graphite, J. Colloid Interface Sci., 2017, 486, 337–343.

126 R. G. Bai, K. Muthoosamy, F. N. Shipton and S. Manickam, Acoustic cavitation induced generation of stabilizer-free, extremely stable reduced graphene oxide nanodispersion for efficient delivery of paclitaxel in cancer cells, Ultrason. Sonochem., 2017, 36, 129–138.

127 H. Naeimia, M. Golestanzadeh and Z. Zarehagha, Synthesis of potential antioxidants by synergy of ultrasound and acidic graphene nanosheets as catalyst in water, Int. J. Biol. Macromol., 2016, 83, 345–357.

128 M. Mirza-Aghayan, M. M. Tavana and R. Boukherroub, Sulfonated reduced graphene oxide as a highly efficient catalyst for direct amidation of carboxylic acids with amines using ultrasonic irradiation, Ultrason. Sonochem., 2016, 29, 371–379.

129 S. Stankovich, R. D. Piner, S. T. Nguyen and R. S. Ruoff, Synthesis and exfoliation of isocyanate-treated graphene oxide nanoplatelets, Carbon, 2006, 44, 3342–3347.

130 J. Jia, Y. Gai, W. Wang and Y. Zhao, Green synthesis of biocompatible chitosan-graphene oxide hybrid nanosheet by ultrasonication method, Ultrason. Sonochem., 2016, 32, 300–306.

131 Y. Hernandez, V. Nicolosi, M. Lotya, F. M. Blighe, Z. Sun, S. De, I. T. McGovern, B. Holland, M. Byrne, Y. K. Gun’ko, J. J. Boland, P. Niraj, G. Duesberg, S. Krishnamurthy, R. Goodhue, J. Hutchison, V. Scardaci, V. A. C. Ferrari and J. N. Coleman, High-yield production of graphene by liquid-phase exfoliation of graphite, Nat. Nanotechnol., 2008, 3, 563–568.

132 J. N. Coleman, M. Lotya, A. O’Neill, S. D. Bergin, P. J. King, U. Khan, K. Young, A. Gaucher, S. De, R. J. Smith, I. V. Shvets, S. K. Arora, G. Stanton, H. Y. Kim, K. Lee, G. T. Kim, G. S. Duesberg, T. Hallam, J. J. Boland, J. J. Wang, J. F. Donegan, J. C. Grunlan, G. Moriarty, A. Shmeliov, R. J. Nicholls, J. M. Perkins, E. M. Griewson, K. Theuwissen, D. W. McComb, P. D. Nellist and V. Nicolosi, Two-dimensional nanosheets produced by liquid exfoliation of layered materials, Science, 2011, 331, 568–571.

133 J. Walter, M. Nishioka and S. Hará, Ultrathin platinum nanoparticles encapsulated in a graphite lattice-prepared by a sonochemical approach, Chem. Mater., 2001, 13, 1828–1833.

134 J. E. Jones, M. C. Cheshire, D. J. Casadonte and C. C. Phifer, Facile sonochemical synthesis of graphite intercalation compounds, Org. Lett., 2004, 6, 1915–1917.

135 L. M. Viculis, J. J. Mack and R. B. Kaner, A chemical route to carbon nanoscrolls, Science, 2003, 299, 1361.

136 J. Guo, S. Zhu, Z. Chen, Y. Li, Z. Yu, Q. Liu, J. Li, C. Feng and D. Zhang, Sonochemical synthesis of TiO₂ nanoparticles on graphene for use as photocatalyst, Ultrason. Sonochem., 2011, 18, 1082–1090.

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137 Y. Cui, D. Zhou, Z. Sui and B. Han, Sonochemical synthesis of graphene oxide-wrapped gold nanoparticles hybrid materials: visible light photocatalytic activity, Chin. J. Chem., 2014, 33, 119–124.

138 S. Zhu, J. Guo, J. Dong, Z. Cui, T. Lu, C. Zhu, D. Zhang and J. Ma, Sonochemical fabrication of Fe3O4 nanoparticles on reduced graphene oxide for biosensors, Ultrason. Sonochem., 2013, 20, 872–880.

139 H. C. Yau, M. K. Bayazit, J. H. G. Steinke and M. S. P. Shaffer, Sonochemical degradation of nmethylpyrrrolidone and its influence on single walled carbon nanotube dispersion, Chem. Commun., 2015, 51, 16621–16624.

140 H. Ha and S. H. Jeong, Facile route to multi-walled carbon nanotubes under ambient conditions, Korean J. Chem. Eng., 2016, 33, 401–404.

141 V. B. Kumar, Z. Porat and A. Gedanken, Facile one-step sonochemical synthesis of ultrafine and stable fluorescent C-dots, Ultrason. Sonochem., 2016, 28, 367–375.

142 K. Wei, J. Li, Z. Ge, Y. You and H. Xu, Sonochemical synthesis of highly photoluminescent carbon nanodots, RSC Adv., 2014, 4, 52230–52234.

143 I. Nissan, V. B. Kumar, Z. Porat, D. Makove, O. Shefi and A. Gedanken, Sonochemically-fabricated Ga@C-dots@Ga nanoparticle-aided neural growth, J. Mater. Chem. B, 2017, 5, 1371–1379.

144 D. W. Jung, D. A. Yang, J. Kim, J. Kim and W. S. Ahn, Facile synthesis of MOF-177 by a sonochemical method using 1-methyl-2-pyrrolidinone as a solvent, Dalton Trans., 2010, 39, 2883–2887.

145 D. A. Yang, H. Y. Cho, J. Kim, S. T. Yang and W. S. Ahn, CO2 capture and conversion using Mg-MOF-74 prepared by a sonochemical method, Energy Environ. Sci., 2012, 5, 6465–6473.

146 A. Mehrani, A. Morsali, Y. Hanifehpour and S. W. Joo, Sonochemical temperature controlled synthesis of pellet-, laminate- and rice grain-like morphologies of a Cu(II) porous metal-organic framework nano-structures, Ultrason. Sonochem., 2014, 21, 1430–1434.

147 V. Safarifard and A. Morsali, Facile preparation of nanocubes zinc-based metal-organic framework by an ultrasound-assisted synthesis method; precursor for the fabrication of zinc oxide octahedral nanostructures, Ultrason. Sonochem., 2018, 40, 921–928.

148 S. A. A. Razavi, M. Y. Masoomi and A. Morsali, Morphology-dependent sensing performance of dihydro-tetrazine functionalized MOF toward Al(III), Ultrason. Sonochem., 2018, 41, 17–26.

149 W. J. Son, J. Kim, J. Kim and W. S. Ahn, Sonochemical synthesis of MOF-5, Chem. Commun., 2008, 47, 6336–6338.

150 Y. R. Lee, S. M. Cho, W. S. Ahn, C. H. Lee, K. H. Lee and W. S. Cho, Facile synthesis of an IRMOF-3 membrane on porous Al2O3 substrate via a sonochemical route, Microporous Mesoporous Mater., 2015, 213, 161–168.

151 S. Dharmarathna, C. K. King’ondu, W. Pedrick, L. Pahalagedara and S. L. Sub, Direct sonochemical synthesis of manganese octahedral molecular sieve (OMS-2) nanomaterials using cosolvent systems, their characterization, and catalytic applications, Chem. Mater., 2012, 24, 705–712.

152 J. A. Thompson, K. W. Chapman, W. J. Koros, C. W. Jones and S. Nair, Sonication-induced oswald ripening of ZIF-8 nanoparticles and formation of ZIF-8/polymer composite membranes, Microporous Mesoporous Mater., 2012, 158, 292–299.

153 O. Abuzalat, D. Wong, M. Elsayed, S. Park and S. Kim, Sonochemical fabrication of Cu(II) and Zn(II) metal-organic framework films on metal substrates, Ultrason. Sonochem., 2018, 45, 180–189.

154 H. M. Xiong, D. G. Shchukin, H. Moehwald, Y. Xu and Y. Y. Xia, Sonochemical synthesis of highly luminescent zinc oxide nanoparticles doped with magnesium(II), Angew. Chem., Int. Ed., 2009, 48, 2727–2731.

155 V. Belova, T. Borodina, H. Moehwald and D. G. Shchukin, The effect of high intensity ultrasound on the loading of Au nanoparticles into titanium dioxide, Ultrason. Sonochem., 2011, 18, 310–317.

156 H. Terraschke, J. Olchowka, E. Geringer, A. V. Rodrigues and C. Wickleder, Facile liquid-assisted strategy for direct precipitation of Eu2+–activated nanophosphors under ambient conditions, Small, 2018, 14, 1703707.

157 K. N. Venkatachalaiah, H. Nagabhushana, G. P. Darshan, R. B. Basavaraj, B. Daruka Prasad and S. C. Sharma, Structural, morphological and photometric properties of sonochemically synthesized Eu3+ doped Y2O3 nanoporphor for optoelectronic devices, Mater. Res. Bull., 2017, 94, 442–455.

158 Y. Li, R. Lei and S. Xu, Combination of ionic liquid and sonication: a fast, mild and green way to fabricate Europium-doped lanthanide nanophosphates, ChemistrySelect, 2016, 1, 4861–4867.

159 J. Yu, J. Yu, W. Ho and L. Zhang, Preparation of highly photocatalytically active nano-sized TiO2 particles via ultrasonic irradiation, Chem. Commun., 2001, 19, 1942–1943.

160 P. J. Jodłowski, D. K. Chlebda, R. J. Jedrzejeczyk, A. Dziedzicka, Ł. Kuterasinski and M. Sitarz, Characterisation of well-adhered ZrO2 layers produced on structured reactors using the sonochemical sol–gel method, Appl. Surf. Sci., 2018, 427, 563–574.

161 A. F. Sierra-Salazar, T. Chave, A. Ayral, S. I. Nikitenko, V. Hulea, P. J. Kooyman, F. D. Tichelaar, S. Perathoner and P. Lacroix-Desmazes, Engineering of silica-supported platinum catalysts with hierarchical porosity combining latex synthesis, sonochemistry and sol-gel process-I. Material preparation, Microporous Mesoporous Mater., 2016, 234, 207–214.

162 A. F. Sierra-Salazar, A. Ayral, T. Chave, V. Hulea, S. I. Nikitenko, S. Perathoner and P. Lacroix-Desmazes, Hierarchical porosity tailoring of sol–gel derived Pt/SiO2 catalysts, Top. Catal., 2018, 61, 1424–1436.

163 D. Manoharan, A. Loganathan, V. Kurapati and V. J. Nesamony, Unique sharp photoluminescence of size-
controlled sonochemically synthesized zirconia nanoparticles, Ultrason. Sonochem., 2015, 23, 174–184.

164 M. Zhang, M. Chen, Y. Liu, Y. Wang and J. Tang, Catalase-inorganic hybrid microflowers modified glassy carbon electrode for amperometric detection of hydrogen peroxide, Mater. Lett., 2019, 243, 9–12.

165 B. M. Teo, S. K. Suh, T. A. Hatton, M. Ashokkumar and F. Grieser, Sonochemical synthesis of magnetic janus nanoparticles, Langmuir, 2011, 27, 30–33.

166 Z. Li, X. Du, X. Cui and Z. Wang, Ultrasonic-assisted fabrication and release kinetics of two model redox-responsive magnetic microcapsules for hydrophobic drug delivery, Ultrason. Sonochem., 2019, 57, 223–232.

167 A. Gedanken, Preparation and properties of proteinaceous microspheres made sonochemically, Chem.–Eur. J., 2008, 14, 3840–3853.

168 X. Du, Z. Li, J. Xia, F. Zhang and Z. Wang, Facile sonochemistry-assisted assembly of the water-loving drug-loaded micro-organogel with thermo- and redox-sensitive behavior, Colloids Surf., A, 2019, 561, 47–56.

169 T. S. H. Leong, G. J. O. Martin and M. Ashokkumar, Ultrasonic encapsulation—a review, Ultrason. Sonochem., 2017, 35, 605–614.

170 Z. Li, J. Dong, H. Zhang, Y. Zhang, H. Wang, X. Cui and Z. Wang, Sonochemical catalysis as a unique strategy for the fabrication of nano-/micro-structured inorganics, Nanoscale Adv., 2021, 3, 41–72.

171 D. Radziuk and H. Moehwald, Ultrasonically treated liquid interfaces for progress in cleaning and separation processes, Phys. Chem. Chem. Phys., 2016, 18, 21–46.

172 S. He, S. Zhong, L. Xu, Y. Dou, Z. Li, F. Qiao, Y. Gao and X. Cui, Sonochemical fabrication of magnetic reduction-responsive alginate-based microcapsules for drug delivery, Int. J. Biol. Macromol., 2020, 155, 42–49.

173 Y. Sun, C. Shi, J. Yang, S. Zhong, Z. Li, L. Xu, S. Zhao, Y. Gao and X. Cui, Fabrication of folic acid decorated reductive-responsive starch-based microcapsules for targeted drug delivery via sonochemical method, Carbohydr. Polym., 2018, 200, 508–515.