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REVIEW

Nickel oxide nanoparticle synthesis and photocatalytic applications: evolution from conventional methods to novel microfluidic approaches

Jiayou Mou[1,2] · Yong Ren[1,2,3,4] · Jing Wang[4,5,6] · Chenxi Wang[7,8] · Yibo Zou[9] · Kexia Lou[9] · Zansheng Zheng[9] · Da Zhang[9]

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Abstract

Nickel oxide (NiO) nanoparticles are essential to developing a wide range of important industrial products, examples of which include electrodes, catalysts, and sensors, leading to diverse applications from electrochemical detection to energy storage and environmental remediation. NiO nanoparticles exhibit higher reaction selectivity under solar-driven conditions. Thus, they are good candidates for photocatalysts, which can generate strong oxidizing and reducing agents for photodegradation of organic pollutants and other target molecules under normal temperature and pressure conditions, giving rise to versatile applications for energy and environmental remediation. The conventional strategies of NiO nanoparticle synthesis can be broadly categorized into three themes: solid-phase method, liquid-phase method, and vapor-phase method. Recently, microfluidic reactors hold great promise for nanomaterial synthesis due to the thermal homogeneity across the reactor and rapid heat transfer ensured by the large ratio of surface area to volume. The exquisite control over the size, structure and composition of the droplet by microfluidic emulsification technology outperforms the traditional microemulsion method. Herein, we present an overview of the latest advances in fabrication of NiO nanoparticles using different approaches including both conventional methods and microfluidic methods, and focus on the fundamentals of each formation process with the main advantages and disadvantages discussed. This review also provides comparative overview of influence of synthesis conditions on size and morphologies of NiO nanoparticles. We also summarized the development of NiO-based photocatalysts in environmental applications. The perspectives for future research are also discussed. It can be envisioned that success in microfluidic method will continue to inspire novel approaches to drive the rapid evolution of the NiO synthesis technologies in future.

Keywords Nickel oxide · Nanomaterials · Microfluidics · Photocatalytic applications

✉ Yong Ren
yong.ren@nottingham.edu.cn

✉ Jing Wang
jing.wang@nottingham.edu.cn

✉ Da Zhang
bobzhang@chemgoo.com

[1] Research Group for Fluids and Thermal Engineering, University of Nottingham Ningbo China, Ningbo, China

[2] Department of Mechanical, Materials and Manufacturing Engineering, University of Nottingham Ningbo China, Ningbo, China

[3] Key Laboratory of Carbonaceous Wastes Processing and Process Intensification Research of Zhejiang Province, University of Nottingham Ningbo China, Ningbo, China

[4] Nottingham Ningbo China Beacons of Excellence Research and Innovation Institute, Ningbo, China

[5] Department of Electrical and Electronic Engineering, University of Nottingham Ningbo China, Ningbo, China

[6] Key Laboratory of More Electric Aircraft Technology of Zhejiang Province, University of Nottingham Ningbo China, Ningbo, China

[7] Chemical and Environmental Engineering, University of Nottingham Ningbo China, Ningbo, China

[8] New Materials Institute, University of Nottingham Ningbo China, Ningbo, China

[9] Ningbo Chemgoo Pharma Tech Co., Ltd, Ningbo, China

1 Introduction

Nanoparticles are ubiquitous in our daily life and are of great interest in several areas, forming the basis for an astounding array of applications of technological and scientific importance. Nanoparticles can be broadly categorized as those with one of its characteristic lengths in the dimension range between 1 and 100 nm. They can be used as nano-building blocks of more sophisticated nanocomposites. The particles with size reduction to nanometer-scale will possess the properties deviated from their bulk ones significantly because of the large specific surface area and unique quantum phenomenon (Greenham et al. 1997; Yang et al. 2019; Wang et al. 2021; Santhi et al. 2004; Stickler et al. 2021), thus possessing remarkably superior advantages in chemical, photology, thermology, and magnetism areas. With the rapid development of nanotechnology, nanoparticles have been widely used in medicine (Kung et al. 2020), biology (Restaino and White 2019; Furtado et al. 2018), electrical engineering (Jayathilaka et al. 2019), sensing (El-Shamy 2021), energy (Ma et al. 2020) and environmental applications (Peng 2002). Therefore, nanoparticles have attracted great interest in recent years and remain a hot research topic in the near future.

The metal-oxide nanoparticle is one of the most important sub-classes of nanoparticles. The past decade has witnessed an explosion in the development of metal-oxide nanoparticles with controlled compositions, sizes, shapes, and structures for industrial applications. For example, titanium dioxide (TiO_2) nanoparticles can remove a range of organic species via photodegradation under UV irradiation, thus it has been widely utilized in environmental pollution mitigation for water purification and air pollution treatment. One can find many excellent review papers on TiO_2 (Palmas et al. 2021; Hasan and Rana 2021; Jaji et al. 2020). NiO is also a burgeoning metallic oxide because it is naturally abundant and environmentally friendly with high thermal and chemical stability (Ghosh et al. 2016). It can be applied as a combustion catalyst (Liu et al. 2017), anode interfacial layer in solar cells (Irwin et al. 2008), anode material in batteries (Li et al. 2021), gas sensors (Yang et al. 2021), and magnetic materials (Kumar and Das 2021). NiO has face center cubic crystal structure and ferromagnetic properties with a Neel temperature of 525 K (Rinaldi-montes et al. 2016a; b). It is a p-type semiconductor with a wide bandgap of 3.6–4.0 eV and possesses peculiar magnetic and electric behavior depending on the particle size (Khatri and Rana 2020; Pooyandeh et al. 2021; Mohseni Meybodi et al. 2012). The unique chemical and physical characteristics render NiO particularly suitable for photocatalytic applications.

Different synthesis methods of NiO electrode material for supercapacitor have been reviewed (Kate et al. 2018), the methods for NiO nanostructure synthesis and characterization of material properties have been reviewed (Bonomo 2018), and the overview has been provided for the synthesis and applications of nickel nanoparticles in size range of 1–100 nm based on solvothermal, physical, and chemical approaches (Jaji et al. 2020).

Microfluidics has emerged as a promising tool in nanomaterial formation, and it is also of importance to assess the application of microfluidics for NiO nanoparticle synthesis, which has not yet been sufficiently reviewed. This motivates us to undertake the review study in a more systematical fashion. The content of the review paper is organized as the following: in the first section, the synthetic approaches for NiO nanoparticles are systematically surveyed, including solid-phase method, liquid-phase method such as direct precipitation method, homogeneous precipitation method, sol–gel method, hydrothermal method, microemulsion method, organic complex precursor method, polymer-network gel method and biosynthesis method, as well as vapor-phase method. In the subsequent section, the principles and applications of microfluidics in fabricating NiO nanoparticles are reviewed. The representative applications using NiO nanoparticles for environmental remediation via photocatalytic approaches are also reviewed and discussed, considering the ever-increasing demands of NiO in renewable and sustainable applications. The summary of NiO synthesis methods and future development perspectives is finally presented.

2 Conventional synthesis methods

The synthesis methods of nanoparticles can be divided into two major types: top-down and bottom-up. The former refers to crushing the bulky material into small-size substances by mechanical techniques, while the latter refers to building the nanoparticles via a chemical process. NiO nanoparticle formation process mainly relies on the bottom-up method through chemical reactions, obeying the classical nucleation theory, which involves three stages: nucleation, growth, and aging (Köhler et al. 2013). Adjusting the temperature of heat treatment, changing the ratio of water or pre-dehydration before the calcination can efficiently avoid nanoparticle aggregation during the formation process (Zhang 2014). The NiO nanoparticle synthesis methods can be classified into the following three categories according to the variations in the reaction media and environment. All the approaches have been intensively investigated to synthesize NiO nanomaterials with tailored composition, size, shape, and crystalline structure.

2.1 Solid-phase method

The solid-phase method is a traditional and long-standing way of fabricating nanomaterials; it has advantages of low cost, solvent-free, high selectivity, and can be applied in industrial production at a relatively mild reaction environment. However, it has drawbacks such as limited accuracy, relatively low efficiency, and difficulty in controlling the particle characteristic properties (Zhang and Qiu 2009). Solid powders are normally used as precursors or reactants. Once homogeneously mixed, the input energy is required to initiate the reaction. Therefore, the high reaction temperature is usually indispensable for the solid-phase method. The microwave reaction system can be applied in solid-phase method, microwave can uniformly radiate to each part of reactants, it can cause the rotation, vibration, and swing of particles, therefore, increasing the efficiency of particles collision, and shortening the reaction time. As shown in Scheme 1, the solid reactants are grinded into powders, then mixed through vibration or rotation, and the heat treatment via calcination is applied to facilitate the pyrolytic reaction before the nanoparticles can be synthesized.

Xia et al. (2015) used nickel nitrate and oxalic acid as reactants with heat treatment at the temperature of 400 °C for 4 h. Wang et al. (2005) used $Ni(OAc)_2{\cdot}4H_2O$ and Tween 80 as the precursor, grinded them into the powder, and then applied the heat treatment by the calcination at 400 °C for 2 h and drying the samples for 4 h under 80 °C. NiO nanoparticles with a well mesoporous structure were synthesized, as shown in Fig. 1. Hosny (2011) produced 8-nm nanoparticles through a semi-solid-phase reaction with a 700 °C decomposition process.

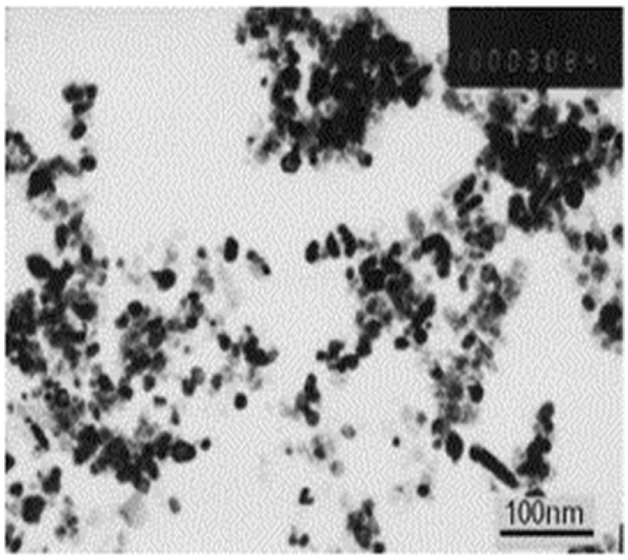
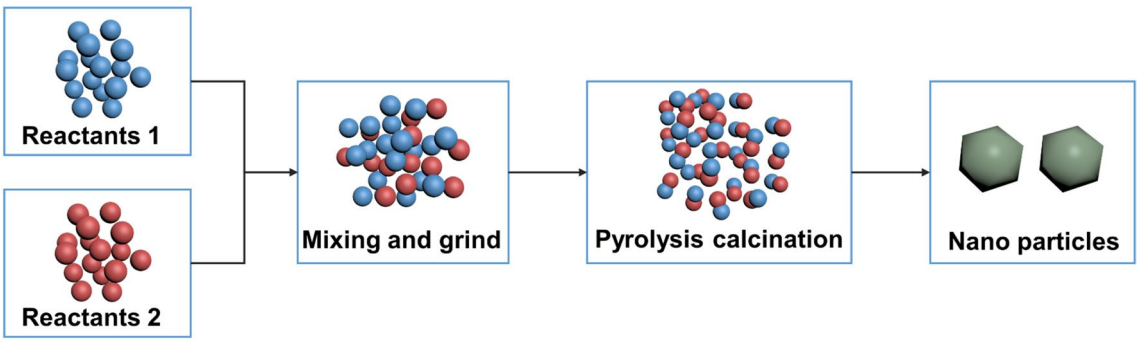


Fig. 1 The TEM of NiO nanoparticle samples synthesized by solid-phase method, reproduced with permission (Wang et al. 2005) from Elsevier

2.2 Liquid-phase method

The liquid-phase method can be classified into several subtypes, such as direct precipitation method, homogeneous precipitation method, sol–gel method, hydrothermal method, microemulsion method, organic complex precursor method, biosynthesis method and polymer-network gel method, according to the different liquid media that have been used. The liquid-phase method mostly uses metallic sault solution to separate the metal element into ions. The heat treatment, hydrolysis, or other processes can be applied to obtain the material precipitation or crystal, and dehydration will turn the precipitation into the target powders (Zhang and Qiu 2009). The NiO nanoparticles fabricated by the liquid-phase method normally feature with relatively uniform distribution of particle size, thus high monodispersity; thus, this method has been most widely used nowadays, owing to the controllable reaction conditions (Karatutlu et al. 2018). The representative samples fabricated by each type of liquid-phase method are shown in Fig. 2.



Scheme 1 The scheme of the solid-phase method using calcination

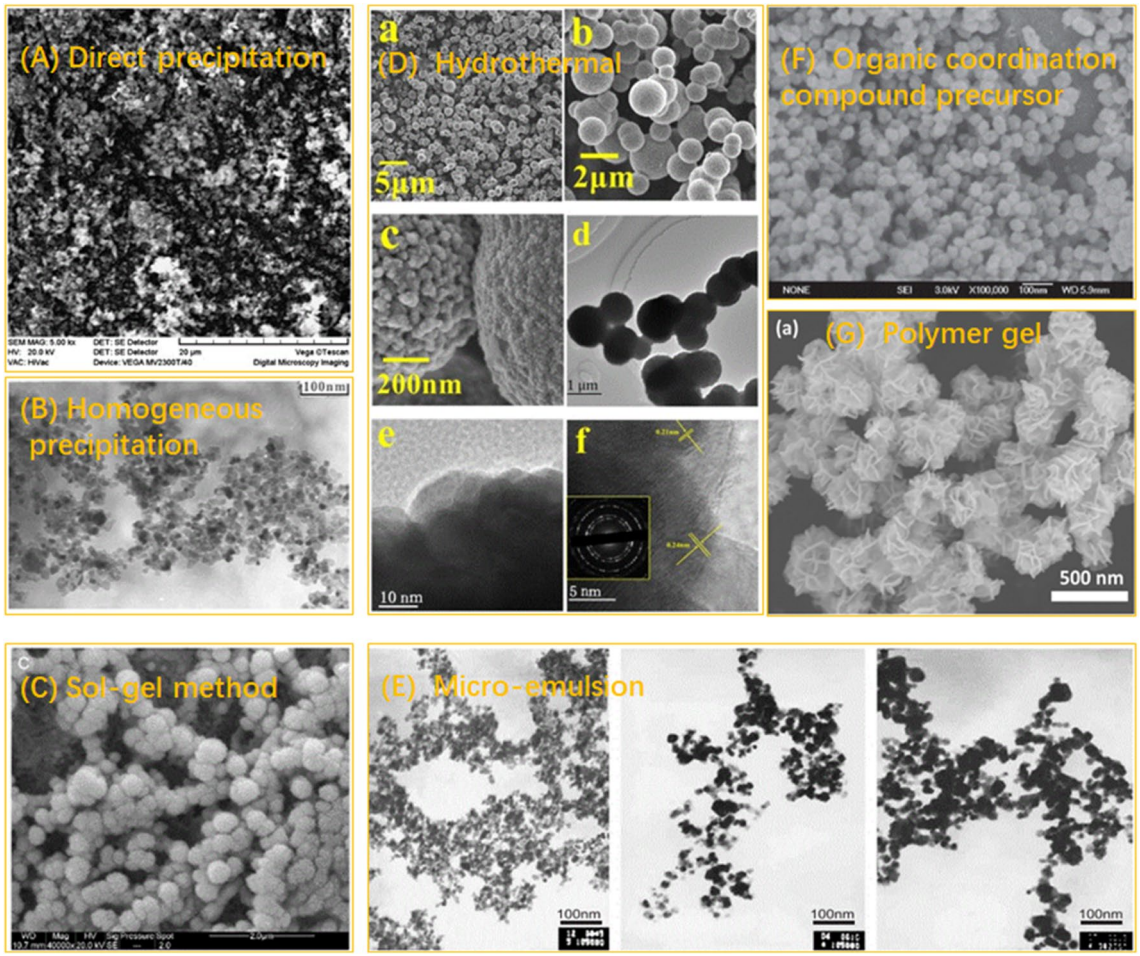


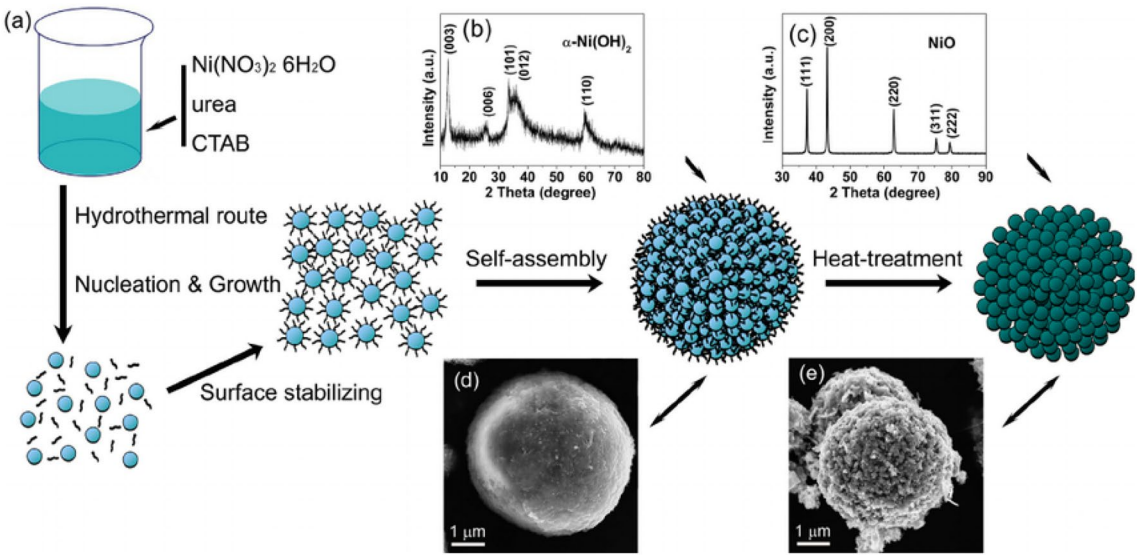
Fig. 2 **A** Scanning electron micrographs (SEM) images of powders synthesized by direct precipitation method. Reproduced with permission (Bahadur et al. 2008) from Elsevier. **B** TEM image of NiO nanoparticles synthesized by homogeneous precipitation. Reproduced with permission (Deng and Chen 2004) from Elsevier. **C** SEM images of sol–gel product. Reproduced by permission (Thota and Kumar 2007) from Elsevier. **D** SEM (a, b, c) and TEM (d, e, f) images of particles synthesized by the hydrothermal method. Reproduced with permission (Cao et al. 2020) from Elsevier. **E** TEM image of NiO nanoparticles synthesized by the microemulsion method. Reproduced with permission (Han et al. 2004) from Elsevier. **F** SEM image of NiO nanoparticles at high magnification (Tao and Wei 2004). Reproduced with permission (Tao and Wei 2004) from Elsevier. **G** SEM images of NiO nanoflowers synthesized by polymer gel method. Reproduced with permission (Munkaila et al. 2021) from Elsevier

2.2.1 Direct precipitation method

The direct precipitation method has been widely adopted in fabricating ultrafine particles. This method uses a chemical reaction to precipitate intact wedges. Then, precipitation will turn into nanopowders through purification, grinding, and heat treatment process (Karatutlu et al. 2018). Bahadur et al. (2008) used sodium hydroxide (NaOH) and nickel nitrate ($Ni(NO_3)_2$) as the precursor, reacting and leading to formation of a wet cake of nanocrystalline NiO, which was subsequently dried and grinded into powders. The grinding process gives rise to big variations in the particle dimension, and distribution of density, thus lacking physical integrality.

2.2.2 Homogeneous precipitation method

The homogeneous precipitation method adopts a principle similar to that of the direct precipitation method; it also used the chemical reaction to produce solid precipitation. However, it keeps the precipitation in solution at a balance condition and makes the precipitate at a uniform speed (Pan et al. 2021). It is attained through controlling the concentration of the precipitant. Therefore, this method is stable, balanced, and able to fabricate high-quality particles. Deng and Chen (2004) fabricated the NiO nanopowders with the purity of 99.73%, cube structure, and averaged size of 9 nm through homogeneous precipitation. Despite the high-quality nanopowders they have synthesized, they used $NiCl_2{\cdot}6H_2O$



Scheme 2 Scheme of hydrothermal decomposition method for producing the NiO nanoparticles. Reproduced with permission (Lv et al. 2015) from Elsevier

solution and $NH_3 \cdot H_2O$ as pre-reactants. The ammoniate products will pollute the environment, so this method needs an extra purification process.

2.2.3 Sol–gel method

This method uses high chemical activity substances as a precursor, through hydrolyze, alcoholization, condensation, and other chemical reactions to get stable sol with relative uniform distribution of the nanoparticles (Kumar and Han 2019; Zorkipli et al. 2016). Then, heat treatment was utilized to obtain metal nanoparticles. The final particles can reach atom level and possess a very small grain diameter. Thota and Kumar (2007) adopted nickel acetate tetrahydrate and oxalic acid as reactants, ethyl alcohol as a solute, undergoing 400 °C calcination. The black powders of NiO nanoparticles were fabricated by Pooyandeh et al. (2021) using the sol–gel methods with nickel nitrate hexahydrate and nickel chloride hexahydrate as the precursor, and magnetic stirring was applied in the fabricate process, after quiescence for a short time, the solution was filtrated to form the NiO nanoparticles.

2.2.4 Hydrothermal method

The hydrothermal method refers to the nanoparticle fabrication process in which a solution was sealed in a high-pressure vessel with the chemical reaction occurring at high pressure and temperature condition, reactants will undergo dissolving, recrystallization, and heat treatment to form the final products (Sree et al. 2020). Scheme 2 shows the typical synthesis mechanisms and procedures of hydrothermal method, the chemical reactions take place in a solution to trigger the formation of the nanoparticles, followed by the heat treatment to remove wastes and obtain the purified products. It has the advantages such as intact development of grain, relative uniform distribution of particle diameter, less aggregation of particles, obviation of calcination at high temperature in the final process, and in particular, it is a cost-effective and facile synthesis process. However, it is more time-consuming than most other methods. Adschiri et al. applied the continuous hydrothermal method for synthesis of 10 various metal-oxide nanomaterials including NiO nanoparticles, using a microreactor with inner diameter of microchannel to be 9.5 mm. They synthesized NiO nanomaterial with an average size of 200 nm in 2 min (Adschiri et al. 1992). Cao et al. (2020) successfully fabricated three hierarchical NiO microspheres through the hydrothermal method. The molar ratio of 1,2-Propanediol and water was kept at 1:1 in the solution. Nickel nitrate ($Ni(NO_3)_2 \cdot 6H_2O$), urea ($CO(NH_2)_2$, and citric acid were chosen as reactants and the ratio was kept at 2:1:1. NiO microspheres were self-assembled and grew in a uniform condition. Nickel nitrate and NH_2CONH_2 are also widely used reactants in the hydrothermal method. An accurate calculation is needed to determine the ratio between each reactant.

2.2.5 Microemulsion method

This method works through two insoluble solvents, for example, oil/water system, to form an emulsion in the presence of a surfactant, or cosurfactants, which can decrease the water/oil surface tension to 1–10 mN m^{-1}, facilitating the formation of emulsions (Malik et al. 2012). Meanwhile,

surfactants and cosurfactants will create a transient interfacial tension to prevent the droplets from coalescence (Ita 2020). The formation of microemulsions normally needs centrifugation or magnetic stirring to accelerate the dispersion process. For example, Han et al. (2004) used cyclohexane as oil phase, Triton X100 as surfactants, and hexyl alcohol as cosurfactants, which were mixed at a ratio of 5:3:2 with the aid of magnetic force to form emulsions effectively.

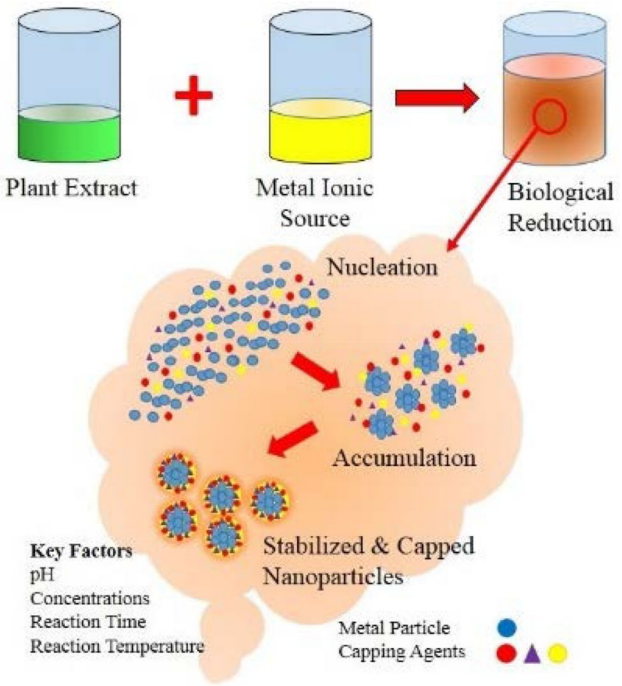
Fabricating nanoparticles through microemulsion method has multiple advantages, such as relatively simple experiment setup, low energy cost, and facile operation. Moreover, the range of particle diameter distribution is relatively narrow, and the particle diameter can be efficiently controlled; second, choosing appropriately different surfactants and cosurfactants can lead to the formation of nanoparticles with a special property (Malik et al. 2012), and the particles will have less aggregation. They are stable due to the presence of surfactants and cosurfactants.

2.2.6 Organic coordination compound precursor method

This method used coordination compounds which are the substances with central metal atoms surrounded by nonmetal atoms (Crichton 2012), and are easy to be removed by pyrolytic reactions as a dispersing agent, then mixed with a metal ion to activate the coordination reaction. During the reaction, the dispersing agent will separate particles and prevent them from agglomeration. The reaction will lead to the fabrication of a highly dispersed precursor, which undergoes heat treatment to produce the target particles. Tao and Wei (2004) selected polymer as a dispersing agent, nickel acetate as reactants, which were mixed to form the precursor at a raised environment temperature of 373 K. NiO nanoparticles were fabricated when the temperature was further raised to 673 K with homogeneous size distribution of around 30 nm as shown in Fig. 2.

2.2.7 Polymer-network gel method

The polymer-network gel method can successfully fabricate the relatively pure phase of NiO particles with a uniform distribution of particle diameter and facile control over the shape of the crystalline grain. The formation of a macromolecular chain will make metal sault ion evenly distributed in the sol–gel. Drying and calcining the sol–gel will lead to the fabrication of the nanoparticles. Liu et al. (2003) adopted acrylamide free radical polymerization and *N*,*N*′-methylene diacylamine bifunctional group using nickel nitrate aqueous solution as raw material, water-soluble propylene Amide monomer and *N*,*N*′-methylene diacylamine act as network agents, ammonium sulfate as initiator, finally, obtaining NiO particles with size ranging in 15–20 nm. Munkaila et al. (2021) synthesized NiO nanoflower using amphiphilic block copolymer as reactants in one-pot synthesis method. The NiO nanoflowers with mesoporous structure were successfully fabricated, as shown in Fig. 2.



Scheme 3 The diagram of biosynthesis principles for forming the metal-oxide nanoparticles. Reproduced with permission of (Shah et al. 2015) from MDPI

2.2.8 Biosynthesis method

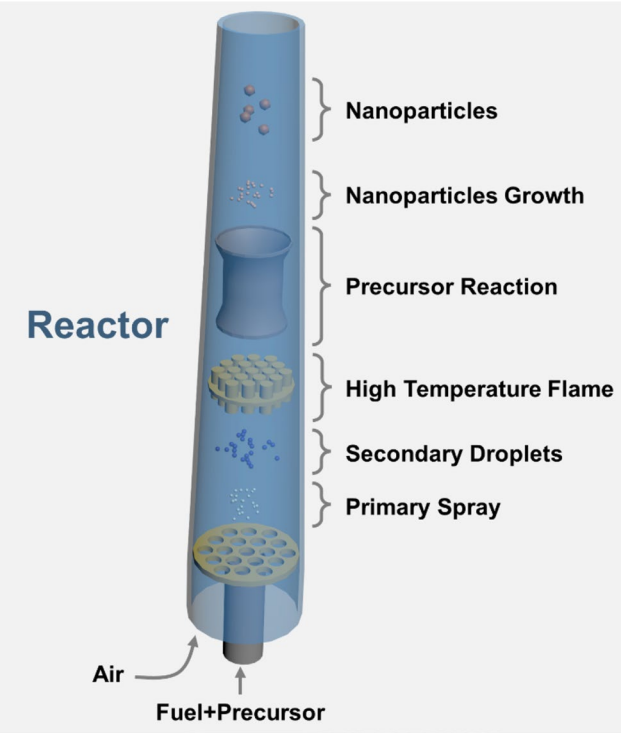
The biosynthesis techniques are very effective in synthesizing metal-oxide nanoparticles. It has drawn much attention as it is both environmentally and economically friendly, it does not require complex operation, and it is innoxious to cell and other biosystems. It uses the small natural molecules in biosystems in combination with the conventional synthesis methods (mainly liquid-phase method) to fabricate nanoparticles and has been proved to have better quality and productivity compared to the conventional methods (Sudhasree et al. 2014; Najjar et al. 2021; Imran Din and Rani 2016; Arumugam et al. 2021). Scheme 3 shows the basic principle of the biosynthesis method. The extract substance of plant can be incorporated in the synthesis process of the nanoparticles. Its pH value, concentration, reaction time, and temperature will directly influence the quality of final products. Sabour et al. (2020) applied the biosynthesis method, using Rheum Turkestanicum plant extractions, and successfully fabricated CeO_2 nanoparticles with average diameter of 30 nm. Similarly, Najjar et al. (2020) used gelatin as stabilizing agent, and sol–gel method to successfully synthesize SnO_2 nanoparticles with an average diameter of 27 nm.

Sabouri et al. used tragacanth as stabilizing agents via the co-precipitation method to synthesize nanosheets with comparable high quality and low toxicity to cells. Its absorption efficiency of anionic dyes and cationic dyes reaches 82% and 60%, respectively (Sabouri et al. 2020a, b). The same group also combined the bio-method with the sol–gel method. They successfully synthesized NiO nanoparticles with an average diameter of 59 nm. They used Arabic gum as stabilizing agent, nickel nitrate ($Ni(NO_3)_2 \cdot 6H_2O$) as reactants, forming an aerogel at 80 °C, enabling the formation of NiO nanoparticles via the biology activities (Sabouri et al. 2021). Therefore, biosynthesis method paves a promising way to synthesize NiO nanoparticles in future.

2.3 Vapor-phase method

The vapor-phase method uses high pressure and temperature vapor to carry the precursor and use its energy to finish the reaction. The most used vapor-phase method is spray pyrolysis, which applies the high temperature and pressure at the nozzle to stimulate the pyrolytic reaction, and the precipitation reaction occurs simultaneously (Wuled Lenggoro et al. 2003). As the metal salt solution sprays out from the nozzle, it will instantly turn into vapor and separate into nanoparticles. Due to the rapid solution evaporation and release of vapor, it is hard to control the particle characteristics such as crystalline shape, particle diameter, and phase purity using this method. However, as it possesses the advantages of a large production rate and facile operation, it has wide industrial production potential (Karatutlu et al. 2018). Scheme 4 shows the different stages of the process. Mixture of air and fuel will provide an environment with high temperature and high pressure, and the precursors are sprayed into droplets prior to the taking place of the pyrolytic reaction and evaporation process. Precursor droplets will start to nucleate and grow to form nanoparticles.

Wuled Lenggoro et al. (2003) used low-pressure spray pyrolysis and successfully synthesized the NiO nanoparticles with an average size of 20 nm. The conversion process and results under different condition are shown in Fig. 3. The solution contains precursor driven by pump going through the channels and is spurted at the nozzle, and the solubility of precursor decides the final type of particles. High-solubility precursor produces nanoparticles, and low-solubility precursor becomes sub-microparticles. Oh et al. (2007) synthesized hollow spherical nanoparticles with uniform distribution of particle diameter of around 20 nm, and well-dispersed nanocrystalline structures. Moravec et al. (2011) fabricated NiO nanoparticles with average diameter about 50 nm by pyrolysis and reduction reaction through 1.5 cm inner diameter nozzle. They proved the production rate include particle size and particle size distribution increase with the increasing of saturation temperature.



Scheme 4 The different stages during the synthesis process of nanoparticles using the vapor-phase method

2.4 The advantages and limitations of conventional methods

Each method has its own advantages and challenges, as summarized in Table 1. The liquid-phase method is the most widely used method in industrial production and lab-scale synthesis. The size of nanoparticles is more uniform and controllable than the solid-phase and vapor-phase methods. The solid-phase method widely uses pyrolysis or microwave, and it is convenient to operate; it has low requirements on the reaction environment and low cost, and the produced particles have a relatively uniform distribution of diameter. However, its quality is relative hard to control and always accompanied by agglomeration. The vapor-phase method has great potential in industrial manufacture, and it has great efficiency with relatively facile operation. However, it has relatively high requirements on the reaction environment and complexity of the devices.

3 Overview of microfluidic systems and applications

Microemulsion has become one of the most effective approaches for nanoparticle formation. However, the traditional methods for microemulsion formation suffer from

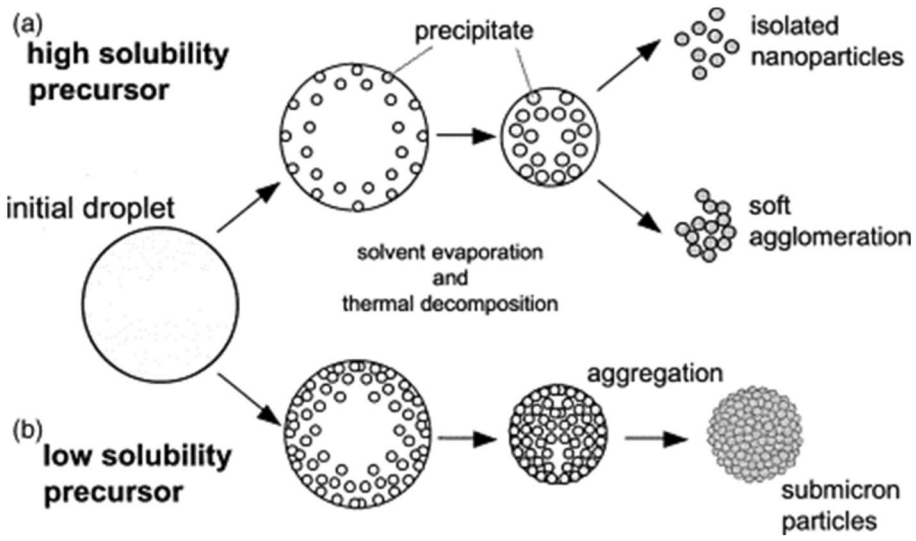


Fig. 3 Conversion process from droplet to particles of low-pressure spray pyrolysis. Reproduced with permission (Wuled Lenggoro et al. 2003) from Elsevier

poor control over the size distribution. An alternative way is to use microfluidics system, in which the fluid flow is constrained in geometry at the microscale, the fluid flow characteristics will undergo significant changes due to the fascinating competition among forces. Parameters describing microfluidic systems can be described by the balance of inertial force, viscous drag forces, buoyant forces, and interfacial tension forces; the balance of each of these forces gives rise to key dimensionless numbers: the Reynolds number (Re), Weber number (We), Bond number (Bo), capillary number (Ca) and flow rate ratio. The viscous force and surface tension will become dominant in the typical flow regimes at low Reynolds number (Bragheri et al. 2016). Microfluidic chips have been applied in biomedicine (Wu et al. 2016a, b), organic synthesis (Zhao et al. 2019), microreactor (Schrimpf et al. 2019), biomimicking (Xu et al. 2020), and chemical analysis (Wu et al. 2016a, b). The microfluidic chip can integrate multiple fluid operations and functions within a portable device at a highly exquisite level (Chen et al. 2021; Stroock 2008; Abedini-Nassab et al. 2021). More demanding applications have been increasing exponentially, and the application areas expand from microreactors for catalysis and chemical synthesis to point-of-care diagnostics, from drug delivery to cell/molecule compartmentalization and diagnostic testing.

In a microdevice, the flows through a microchannel and can be manipulated in a droplet-wise dispersed way (Lian et al. 2020a, b; Lim et al.2017; Ren and Leung 2016; Ren et al. 2015) or a continuous way (Leung and Ren 2014; Ren et al. 2013; Ren et al. 2013; Leung and Ren 2013). The droplet microfluidics has been widely used in producing microcarriers (Choi et al. 2016a, b), microcapsules (Shirk et al. 2013), and cell-laden microgels (Choi et al. 2016a, b), because fast reaction times in such small compartments are induced by the high surface area to volume ratios, efficient heat and mass transfer, and short diffusion distances. This mechanism can form droplets with uniform size distribution in a very narrow range. Droplet microfluidic device is composed of microchannels and microchambers (Ren et al. 2013). A wide range of materials such as metal (Singh et al. 2010), silicon (Singh et al. 2010), glass (Campbell et al. 2020), polymers (Boodaghi and Shamloo 2020), and ceramics (Malecha et al. 2019) have been used to fabricate microfluidic devices. Each material has its own advantages, demerits, and application areas. For example, metal has the advantages such as low cost, ease machining, and high stiffness. However, it is relatively hard to monitor the status of inner fluid and reaction because it is not transparent (James et al. 2020). Using silicon-based materials for microfluidic chips enables multiple advantages as it is stable, easy to design, and it has special semiconductor characteristics. However, its transparency and price remain big problems (Singh et al. 2010). Glass has perfect transparency and chemical stability along with other advantages' however, its high fabrication expense hinders its application in making microdevices (Niculescu et al. 2021a; b). Ceramics has unique chemical properties and high-temperature stability; however, due to the restriction of porosity, processing techniques, and brittleness, it is relatively hard to use (Singh et al. 2010). Polydimethylsiloxane (PDMS) is one of the most well-known polymer materials used in microfluidics because it is cheap, easy to design, mechanically flexible, and chemically stable, making it a very popular material in lab on a chip areas, however, it still has the problem of molecular diffusion and porosity (Nielsen et al. 2020). The technique used in the fabrication of microfluidic devices is, therefore, material dependent. Glass and silicon are mainly used by chemical methods, for example, wet and dry etching and electrochemical discharge machining (Hwang et al. 2019). Other materials like metals, are mainly used

Table 1 Summary of merits and limitations of conventional NiO synthesis methods

Fabrication methods	Average particle size (nm)	Effective temperature (degree Celsius)	Synthesis duration (hours)	Merits	Limitations	References
Solid-phase method	8	700	4.3	Low cost, facile operation, no solvent, high selectivity, high yield	Large energy consumption, low efficiency, vulnerable to oxidation deformation	Hosny (2011)
	10	400	6.5			Wang et al. (2005)
Direct precipitation method	9	300	13	Acceptable cost with relative high purity of product, good stoichiometry	Low power density with poor physical integrity	Barakat et al. (2013)
Homogeneous precipitation method	9	400	3.5	Low cost, facile operation, stable reaction, and high quality of product	Stringent requirements on reaction environment and post-processing including centrifugal deposition, mixed crystal co-precipitation, and extra purification process	Pan et al. (2021)
Sol–gel method	19	400	> 28	Facile operation. uniform particle size distribution, and high chemical activity	Relatively high cost with accurate control over solution concentration, sol–gel temperature, and heat treatment temperature	Pooyandeh et al. (2021)
	4–22	500	28			Zorkipli et al. (2016)
Hydrothermal method	15–20	400	16.6	Particle diameter is small with monodispersed distribution, less agglomeration	Requirement of stringent control over solution concentration, reaction duration and temperature	Sree et al. (2020)
Microemulsion method	3–15	450	25.5	Monodispersed particle size distribution	Requirement of surfactants and cosurfactants, relatively high cost	Han et al. (2004)
Organic complex precursor method	Around 30	400	-	Uniform particle size distribution with good dispersion performance	High cost and requirements on material and chemicals	Tao and Wei (2004)
Polymer-network gel method	Mostly < 40	500	31	High purity of products, good control over the particle size	High cost and low operation accuracy	Liu et al. (2003)
	Mostly 210	350	> 15			Munkaila et al. (2021)
Vapor-phase method	Around 20	900	< 1	High productivity with high potential in industrial scale production, fast reaction process	Difficulty in controlling the morphology of solid particles, stringent requirements on instrument and devices	Wuled Lenggoro et al. (2003)
	14	400	About 20			Oh et al. (2007)
Biosynthesis method	59	500	18	Low biotoxicity, applicable in cell and bio-engineering, facile operation and experiment process	Relatively high cost with accurate control over solution concentration, reaction duration, reaction temperature, the substance from plant extraction may pollute the reaction environment	Sabouri et al. (2021)

in mechanical processes, for example, micromachining (Faustino et al. 2016), micro-milling (Faustino et al. 2016), ultrasonic machining (Hwang et al. 2019), blasting (Jáuregui et al. 2010), injection (Gale et al. 2018), and polymers are normally used by soft lithography.

Microfluidics technology has been drawing a lot of attention since the early 1990s (Manz et al. 1990), and it has been applied to create a stable pre-reaction environment for chemical reactions. In addition, microfluidics can also efficiently separate different substances in a solution by the characteristic properties such as the density difference, examples including plasma separation, circular tumor cell capture, and detection (Wu et al. 2016a, b). Microfluidic technology has evolved rapidly in the past decade and demonstrated to be a promising solution with the capability to conduct multiple biological or chemical reactions in parallel, thus accelerating measurement outcomes of the conventional laboratory tests (Niculescu et al. 2021a; b), such as fast detection of circulating tumor cells (Xu et al. 2020) and environmental detection and remediation (Yew et al. 2019; Lian et al. 2020a, b). In addition, microfluidics has versatile control over the flow conditions, giving rise to the ability to synthesize micro/nanostructured materials with high monodispersity in size and shape distribution (Lian et al. 2018). Microfluidics has been widely used in biology and biomedical engineering for studies related to genes, cells, and proteins. The combination of microfluidics with biomolecular and tissue engineering provides a new direction for simulating the human internal environments (Tian et al. 2019) and biomimicking in vivo environments (Xu et al. 2020).

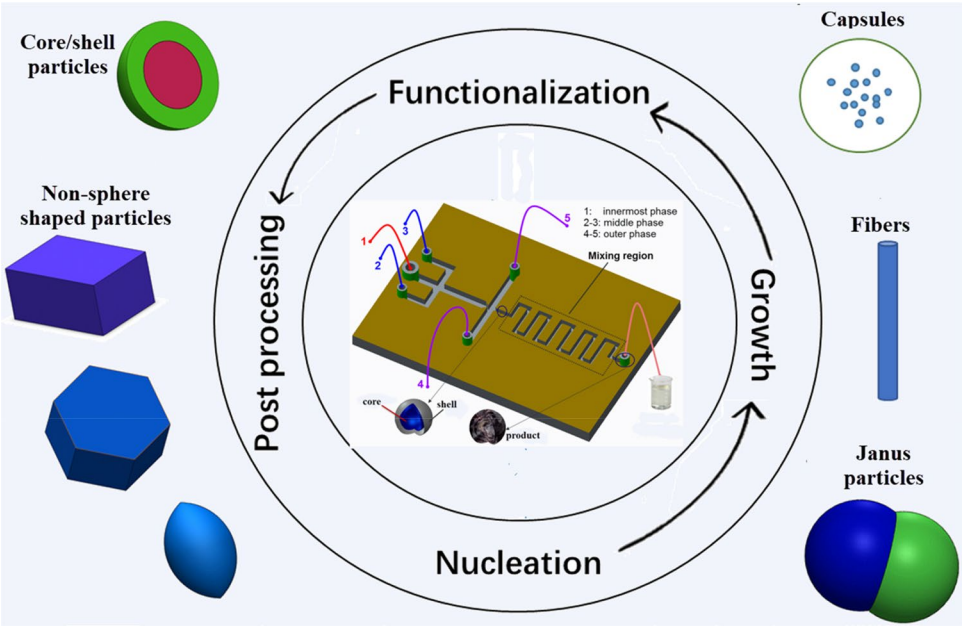
4 Fabrication of nanoparticles using microfluidic technology

The nanomaterial formation process can be achieved using a microfluidic platform with accurate control and monitor over the nucleation and growth of nanoparticles (Jensen 2017). Zhang et al. (2017) provided an overview on mixing, flow dynamics, and mass and heat transfer in microreactors along with three strategies for scaling-up microreactors: parallel numbering-up, consecutive numbering-up, and scale-out. They also proposed a possible methodology to design microchemical systems. Wang et al. (2014) had developed a new strategy for scaling-up of a microsieve dispersion reactor. Deposition methods can be applied to create a thin coating on the particles surface and form a layered structure (Jocic 2016), it has been widely used in food (Wang et al. 2018), medicine (Dai et al. 2021), textiles (Yip and Luk 2016), materials (Zhang et al. 2014) and environmental protection. Zhao et al. (2020) successfully used a microfluidic interfacial synthetic method to fabricate covalent organic polymer microcapsules, and it has been widely used in wastewater treatment and environmental protection.

Microfluidics can produce particles with high purity, complex structures and a highly evenly distribution of particle sizes. Lian et al. (2020a, b) successfully applied microfluidics in fabricating TiO_2 nanoparticles through surfactant wrapping sol–gel method, with TiO_2 nanoparticles evenly distributed on the outer surface of the multiple wall carbon nanotubes (MWCNTs), and it has the ability to absorb Rhodamine B for wastewater treatment. Du et al. (2011) fabricated SiO_2 nanoparticles using membrane microreactor, they suggested a gas–liquid precipitation reaction system which can guarantee the quality meanwhile saving the cost. The same group improved the synthesized process of $BaSO_4$ by adding microbubbles created by the microreactor (Du et al. 2013). $CaCO_3$ nanoparticles were fabricated by Wang et al. (2007) via integration of a microstructured reactor and the microfluidics to enhance mass transfer in the mixing process. It is feasible to apply microfluidic technology in the synthesis process of NiO nanoparticles. Most nanomaterial growth process involves three steps: nucleation, growth, and aging. As shown in Scheme 5, the microfluidic system enables accurate control over the flow conditions of different phases which are pumped into the microchannels, and the synthesis of nanomaterials can be achieved in the microreactors, with yielded products adopting different forms such as sphere-shaped, non-sphere-shaped particles and capsules, and fibers. The microfluidic platform provides a powerful mixing ability that can significantly stimulate the nucleation process. Besides, the stable fluid flow environment is suitable for the growth of large size particles and the formation of complex-shaped particles (Chen et al. 2021).

Another attribute making microfluidics competitive for synthesizing NiO nanoparticles is that as the synthesis reaction of nanoparticles is mainly chemical reaction dominant, less time-consuming procedures will be favorable, and this can benefit from rapid mixing of reactants which can be achieved using microfluidic platforms. Liu et al. (2014) used microfluidic reactors connected in series for fabricating $AlPO_4$-5 which is a very important crystalline microporous aluminophosphate material, the single-phase $AlPO_4$-5 was produced in 1 min. In comparison, it will take the conventional methods, such as the hydrothermal methods, a few days to fabrication the same products. Furthermore, the same group used a millimeter-sized continuous flow reactor to synthesize ZSM-5 (Liu et al. 2016). The reaction time has been successfully shortened into seconds.

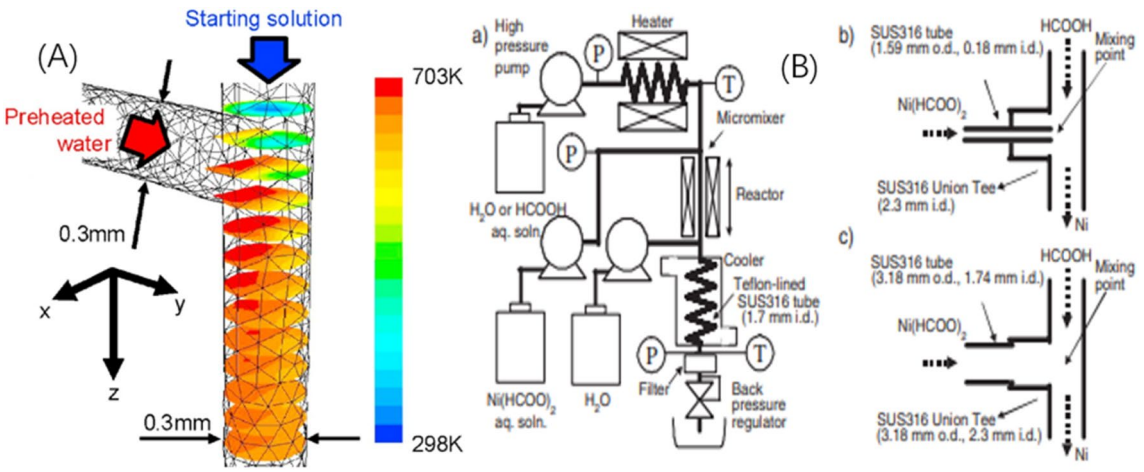
The rapid development of microfluidic reactor makes it possible to fabricate complex structured nanoparticles with an accurate control over the process. Liang et al. (2020) developed a continuous mode microfluidic reactor, which can effectively enhance heat transfer and mixing. They successfully synthesized $Ni_{0.6}Mn_{0.2}Co_{0.2}CO_3$ with uniform



Scheme 5 Nanomaterial synthesis process based on microfluidic technology

particle size distribution, good thermal stability, and homogeneous transition metal distribution. As the NiO nanoparticle fabrication process normally involves high pressure, either the number of channels could be increased, the channel cross-section could be enlarged, or the flow rate in the channels could be increased to cope with a high mass flow rate (Kockmann et al. 2006). Ceramics microreactors can be used when high temperature is required for the formation of NiO nanoparticles.

Kawasaki et al. (2010a, b) used a T-shaped micromixer and successfully applied a continuous supercritical hydrothermal method to synthesize NiO nanoparticles with size of 20–50 nm. Meanwhile, when they decreased the tube diameter from 2.3 to 0.3 mm, the size of NiO nanoparticles changed from 54.3 to 20.1 nm. Sue et al. used a central collision type micromixer for synthesis of Fe_2O_3 and NiO nanoparticles. They investigated the effects of the key factors such as residence time and temperature in the synthesis process. They used $Fe(NO)_3$ and $Ni(NO)_2$ as reactants in the continuous hydrothermal method and successfully fabricated nickel ferrite with a diameter less than 5 nm (Sue et al. 2011a, b). They also used a 0.3 mm T-shape micromixer to successfully fabricate NiO nanoparticles with an average diameter of 16 nm. They used preheated water flow in the T-shape tube to provide the energy for the hydrothermal reaction shown in Scheme 6 (Sue et al. 2011a, b). Kiwamu



Scheme 6 **A** Temperature contour of T-shape mixer. Reproduced with permission of (Sue et al. 2011a, b) from Elsevier. **B** (a) Schematic diagram of reaction flow system, (b) newly designed T-shape mixer, (c) conventional T-shape mixer. Reproduced permission of (Kiwamu et al. 2009) from Springer

et al. (2009) invented a new type of micromixer for synthesis of nanoparticles. As shown in Scheme 6B, they adopted a T-shaped micromixer with the tube inner diameter to be 0.18 mm. The completed flow system consists of the pumps, reactor and other devices. The micromixer was positioned at upstream of the reactor, the powerful mixing ability of the microfluidic mixer provided the highly uniform mixture solution. With hydrothermal reaction, they used this new mixer to achieve the fabrication of NiO nanoparticles with size of 18.2 nm and 23.5 nm, respectively. Kawasaki et al. (2010a, b) developed a new swirl micromixer for synthesis of NiO nanoparticles. Compared to a conventional T-shaped mixer, the average diameter of particles has been reduced from 47 to 20 nm with monodispersed size distribution. Moreover, computational fluid dynamic simulation results suggested that the swirl mixer can enable rapid and homogeneous mixing of fluids, therefore, producing high-quality nanoparticles. Zhao et al. (2015) constructed various NiO nanoarrays through Y-shaped needles, and they used a pump to drive the solution flow through the needles; then, the reactions occurred in microtubes to form nanosheets with a thickness of about 40 nm; they used the nanosheets to modify microchannels to enhance its ability to absorb protein. Xia et al. used the aerosol decomposition method in microreactor with inner diameter of 13 mm to successfully fabricate NiO nanoparticles with an average size of 10 nm. Furthermore, they investigated the influence of the addition of salts (Xia et al. 2002). Lu et al. (2019) reported the synthesis of NiO nanoparticles with size of 4–6 nm encapsulated in the carbonization of eggshell membrane using a green and facile approach for hydrogen evolution reaction electrocatalysts. The eggshell was applied as the microreactor. They also synthesized NiO/C nanocomposites with higher catalytic activity and smaller Tafel slope. The method can dispose eggshell waste and synthesize NiO nanoparticles simultaneously. Yoko et al. (2020) applied a T-shaped micromixer system to investigate the correlation between the mass transfer rate and Reynolds number and the kinetics under reaction control conditions, and evaluated the reaction kinetics of synthesis for the nickel nitrate to nickel oxide reaction that took place in a wide range of temperatures and pressures around the critical point of water. The NiO nanomaterials with diameter ranging in 10–40 nm had been fabricated. Xu (2017) investigated the most appropriate mixer design for a novel two-stage reactor by computational fluid dynamics modeling, constructed a two-stage continuous hydrothermal flow synthesis microreactor for synthesis of different metal oxides including NiO nanoplates with thickness of 3.4–54.3 nm. Michalska et al. (2021) deposited high-quality NiO film with thickness of 30 nm using a Tesla-valve micromixer. The key synthesis conditions for NiO nanomaterial formation using microfluidic reactors are summarized in Table 2 which demonstrates that the morphology and size of NiO nanomaterials can be well tuned via control over the flow rate and the dimensions of the microreactor systems.

In summary, microfluidics has the intrinsic superior ability in enhancing mixing, heat, and mass transfer and provides a stable chemical reaction environment, giving rise to these advantages as follows:

1. Microfluidics enables high mixing efficiency even in laminar flow at low Reynolds number. It can accelerate the formation of precursor and shorten the reaction time significantly. Meanwhile, a microfluidic mixer, either in a passive or active way, can rapidly lead to homogeneous mixing of reactants, hence enhancing the quality of the final products.
2. Stable flow environment can facilitate the reaction with very stable conditions. A microfluid reactor with a uniform fluid flow can provide a very stable chemical environment, which is suitable for NiO nanoparticle synthesis.
3. Improved heat transfer ability can decrease the energy loss and make the reaction take place rapidly; most synthesis methods of NiO nanoparticles need heat treatment, microfluidic reactor accelerates the process of heat transfer and facilitates the nucleation and growth of nanoparticles.

Table 2 The summary of key synthesis conditions for NiO nanomaterial formation using microfluidic reactors

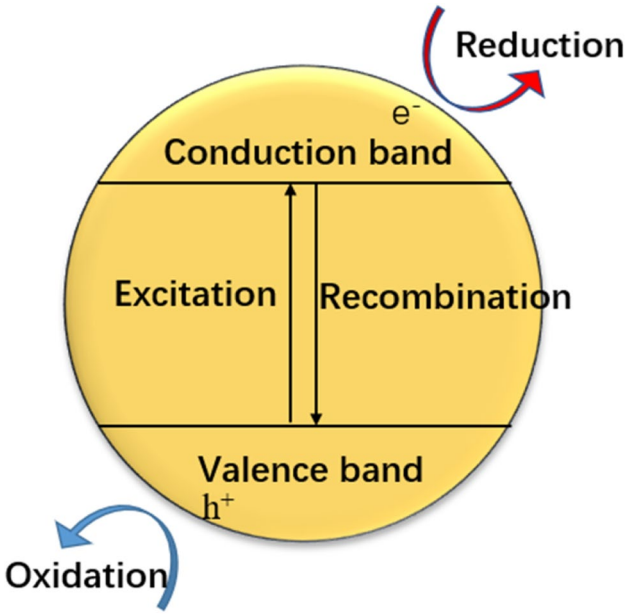
Shape of NiO nanomaterials	Size of NiO nanomaterials	Flow rate	Channel size of microreactors	Flow residence time	References
Nanoplate	20.1–54.3 nm in thickness	30 mL/min	0.57 mm	1.3–2.7 s	Xu (2017)
Spherical nanoparticle	4–6 nm in diameter	/	Eggshell membrane reactor with 70 μm in thickness	~8 h	Lu et al. (2019)
Nanofilm	30 nm in thickness	50–100 μL one time	1–3 μm	< 10 s	Michalska et al. (2021)
Array	40 nm in thickness	25 μL/min	530 μm	400 min	Zhao et al. (2015)
Spherical nanoparticle	10–40 nm in diameter	38.7 g/min	0.3 mm	< 1 s	Yoko et al. (2020)

The detailed comparison between conventional synthesis methods and microfluidic synthesis methods has been shown in Table 3. Compared with the conventional methods, the microfluidic technology provides a number of merits for nanoparticle synthesis, such as highly monodispersed particle size distribution, and more accurate control over the particle size and the particle loading efficiency by tuning the flow and reaction conditions, as well as the microreactor dimensions (Shepherd et al. 2021).

Owing to the exquisite control over the particle diameter, shape, and other properties in a tunable way, microfluidic systems have been demonstrated to be useful platforms for synthesizing nanoparticles of organic polymers, oxides, semiconductors, and metals as well as hybrid structures combining multiple materials and functionalities. Despite the rapid development of microfluidic technologies for nanomaterial synthesis, the novel approach still faces some challenges. First, it is important to identify and understand the mechanisms of channel clogging, such as constriction by deposition and accumulation on the walls or particle agglomeration, which remains challenging during the material synthesis process via the microfluidic approach. The microdevices will have to be cleaned thoroughly or even completely replaced by a new one. The surface modifications and flow modulation can potentially address these issues. For example, the contact between reactants and microreactor wall can be minimized using droplet flow or applying special coating on the reactor wall can efficiently isolate control the particle agglomeration (Zardi et al. 2021). Mitigation of the clogging in microchannels can also be achieved using pulsatile driven flow instead of static flow and this will significantly delay the formation of clogging (Dincau et al. 2022). Second, the throughput of microfluidic approach remains far from meeting the practical industrial demands. This challenge can be addressed by scale-up approach via increasing the number of devices running in a parallel mode. Third, the design of microfluidic chips requires substantial efforts to explore the optimal parameters, such as the number of microchambers and channel size (length, width, height). In addition, the fabrication process of microfluidic chips greatly relies on expensive laboratories and extremely sophisticated instruments (Niculescu et al. 2021a, b). Therefore, the development of microfluidic technology for nanomaterial synthesis requires more in-depth investigations and multidisciplinary integration of material science and fluid mechanics in particular. An effective way to address the fabrication challenge is to apply the commercially available off-shelf devices to build the micromixers and micropumps, this will obviate the need of photolithography method and clean room; therefore, it will significantly decrease the fabrication cost.

Table 3 Summary of the advantages and disadvantages of conventional method and microfluidic methods

	Conventional methods	Microfluidic methods
Reaction time	Relatively long: a few hours for mixing reactants to fabricate precursors; and several hours for the nanomaterial formation process	Significantly reduced reaction time due to the enhanced heat and mass transfer and rapid homogeneous mixing capability
Device requirements	Most solid and liquid-phase methods have low requirements on devices. The vapor-phase method has relatively higher requirements on devices	High requirements on the size of the microtube or microchannels in the microreactor
Flow conditions	Mostly batch mode multiphase flow environment. For example, sol–gel method needs the samples to be transferred and dried for a long time; therefore, it is not appropriate to be applied into continuous synthesis. Only a few conventional methods such as spray pyrolysis and supercritical hydrothermal methods enable continuous NiO synthesis	Mostly dynamic multiphase flow environment in the mixing process and the reaction process; therefore, microfluidics is competent for continuous mode formation of NiO nanomaterials
Production rate	The vapor-phase method has a relatively high production rate. Most liquid- and solid-phase methods have a relatively limited production rate	Easy to scale-up by continuous synthesis in parallel mode
Material restrictions	A wide range of reactants in solid phase, liquid phase and vapor phase can be applied	Suitable for liquid-phase reactants with relatively low viscosity
Nanoparticle size uniformity and product material property discrepancy	More challenging to control the particle size distribution, relatively high property discrepancy from batch to batch	The precise control over the flow conditions and more uniform pressure and temperature distribution in confined reaction domain gives rise to high particle size monodispersity and low property discrepancy
Reactant consumption	Relatively high	Low reactant consumption as the reaction occurs in the microscale with high reaction efficiency



Scheme 7 The schematic of kinetic processes of photocatalysis

5 Photocatalytic applications of NiO nanomaterials

Photocatalysis is capable of photodegradation of the organic contamination, and the light absorption involved process can accelerate a photo-reaction by a catalyst, which has no change in itself and is not consumed during the chemical reactions. Photocatalysis is an eco-friendly technique to address energy and environmental challenges (Koe et al. 2020). Semiconductor metal oxides such as NiO (Sun et al. 2018), TiO_2 (Wang et al. 2020), MoS_2 (Chandrabose et al. 2021), ZnO (Abdullah et al. 2020), and Al_2O_3 (Li et al. 2016) can be activated by exposure to UV–visible light appropriate to its bandgap energy to catalyze a redox reaction at its surface. As shown in Scheme 7, the electrons of a semiconductor are excited from the valence band (VB) to the conduction band (CB) by photoluminescence. The photoelectrons and holes subsequently experience spatial separation and transfer to their acceptors. The oxidation and reduction reactions will require more positive hole potential and more negative CB potential to favor the reactions (Liu et al. 2020; Byrne et al. 2015). Recently, NiO have been used as photocatalyst to degrade organic dyes, such as methyl orange (MO) and methylene blue (MB) (Ma et al. 2021). The electron and hole formation will contribute to oxidize/reduce organic pollutants, while the holes of NiO surface will adsorb and trap water molecules, with the causation of hydroxyl radicals oxidation. At the same time, the oxygen molecules produce anionic superoxide radicals, which will degrade MB and MO to CO_2, and H_2O (Sabouri et al. 2020a, b).

Among the transition metal oxides, TiO_2 is a very good photocatalyst and has been used in many photocatalytic systems, due to the high photoconversion efficiency, high stability, and high specific surface area (Shrestha et al. 2010). However, the efficiency of TiO_2 is limited by wideband energy which is closed to 3 eV, and fast recombination of photo-generated electrons and holes, indicating only about 5% of the solar energy spectrum can be used (Mohapatra et al. 2007; Jasim et al. 2020). NiO is a p-type semiconductor with low cost, high optical transmittance, high specific surface area, and can be shaped into complex structures (Chinnappan et al. 2018). It can form a p–n junction material with an n-type semiconductor. The electric field arising from the p–n junction via the combination of p-type and n-type semiconductors can significantly restrain the recombination of photo-generated electrons and holes. NiO nanoparticles can significantly enhance the photocatalytic hydrogen evolution from aqueous methanol because NiO nanoparticles exhibit high activity attributed to ease of trapping photo-generated electrons (Wu et al. 2014; Faisal et al. 2018); therefore, the combination of NiO and TiO_2 can significantly increase the efficiency of photocatalyst. This approach can also be extended to other n-type semiconductors, such as SnO_2 (Suvith et al. 2020) and ZnO (Abdullah et al. 2020). Hu and Teng (2010) loaded NiO on n-type $NaTaO_3$ to trigger the water-splitting reaction under UV light exposure, the final production rate of H_2 reached 9000 μmol g^{-1} h^{-1}. Sun et al. (2021) used p–n heterojunction between NiO and Cadmium Sulfide (CdS) to induce hydrogen spillover effect, remarkably improving the H_2 evolution performance with production rate to be 243.9 mmol/g/h. In addition, NiO as cocatalyst not only can cooperate with a metallic oxide but also with another catalyst to induce a synergetic effect. Liu et al. (2018) loaded NiO on the surface of g-C_3N_4, the created C–O–Ni bond significantly improved hydrogen evolution and stability, the inner electric field created by heterojunctions can drive the migration of the photo-generated electrons through the C–O–Ni linkage from g-C_3N_4 to NiO, which facilitated the charge separation. Khatri and Rana (2020) adopted Fe doping on the NiO nanoparticles through the chemical co-precipitation method to form photocatalysis dyes. It largely increased the photocatalysis efficiency and can be considered as promising photocatalysts for organic pollutant treatment. Lin et al. (2018) applied two-dimensional amorphous NiO nanostructure instead of nanocrystal NiO particles in solar H_2 evolution, the NiO nanoparticles can work alone as a photocatalyst and functions stably and efficiently in the chemical reactions. Table 4 shows the representative applications using NiO as the photocatalysts or co-photocatalysts, and it demonstrates that the addition of NiO can significantly improve the photocatalytic efficiency. NiO nanoparticles with high photocatalytic activities can be used as self-cleaning transparent nanocoating for solar

Table 4 Summary of synthesis methods and photocatalytic efficiency of NiO-based photocatalysts in environmental applications

NiO synthesis methods	Catalyst substance	Applications	Catalyst efficiency rate	Efficient wave length	References
Chemical deposition method	Single-crystal CdS nanorods with NiO shell	Hydrogen generation	Hydrogen generation efficiency improves by 1090%	365 nm	Sun et al. (2021)
Synthesis of $Ni(OH)_2$ by impregnation method and post-annealing	g-C_3N_4 and amorphous NiO	Hydrogen generation	Hydrogen generation efficiency improves by 43,000%	380 nm	Liu et al. (2018)
Laser ablation of bulk NiO powders	Two-dimensional amorphous NiO	Hydrogen generation	Hydrogen generation rate increases to 1008.46 μmol/h	532 nm	Lin et al. (2018)
Pyrolysis of the mixture of Na_2CO_3 and $Ni(NO_3)_2{\cdot}6H_2O$	$NaTaO_3$ and NiO particles	Hydrogen generation	Hydrogen evolution rate increases to 9000 μmol/h/g	310 nm	Hu and Teng (2010)
Chemical co-precipitation method	Iron and NiO nanoparticles	Photocatalytic degradation of methylene blue and rose bengal dyes	Degradation efficiency reaches 86% and 85%, respectively	540 nm and 664 nm, respectively	Khatri and Rana (2020)
Annealing of the precipitate synthesized by mixing of SnO_2 nanoparticles, Nickel (II) acetate and tannic acid	SnO_2 and NiO	Degradation of methylene blue and eosin yellow dyes	Degradation efficiency reaches 98% and 97%, respectively	664 nm and 517 nm, respectively	Suvith et al. (2020)

cells to prevent the deposition of dust and air pollutants on the solar cells over time. It can be envisioned that NiO nanoparticles can find more diverse applications, especially in environmental fields.

6 Conclusions and outlook

NiO nanoparticles have attracted increasing attention because of unique chemical and physical properties. We provide a comprehensive review of the state-of-art synthesis methods of NiO nanoparticles, combining both the conventional methods and the latest advances in applying microfluidics as a promising alternative for the highly efficient synthesis of NiO nanoparticles.

The liquid-phase method is the most widely used method in industrial production and lab-scale synthesis. The size of nanoparticles is more uniform and controllable than the solid-phase and vapor-phase methods. With the development of microfluidic technology, the traditional synthesis method can be improved to achieve a higher production rate, expanded range of applications, and higher product quality. Moreover, the integration of multiple functions on the chip-based microfluidic systems shows a promise for the holistic realization of nanoparticles with demanded optical, electronic, and catalytic properties by controlling the channel geometries and flow conditions. Nevertheless, the novel approach still faces some challenges. First, it is important to identify and understand the mechanisms of channel clogging, and mitigate the problem by surface modifications and flow modulation. Second, the throughput of microfluidic approach remains far from meeting the practical industrial demands. This challenge can be addressed by scale-up approach via increasing the number of devices running in a parallel mode. Third, the fabrication process of microfluidic chips greatly relies on expensive laboratories and extremely sophisticated instruments, and this can be addressed by applying the commercially available off-shelf devices to build the micromixers and micropumps in the microreactor systems. Accuracy and repeatability are also very crucial, and it is expected that automated apparatus should be used as much as possible without much intervention from human operators to ensure the quality consistency of NiO nanoparticles during the production process from one batch to another batch. More efforts are, therefore, required in the future to develop microfluidics based technologies for NiO nanoparticle synthesis in a more cost-effective and energy-efficient way, as well as exploring their photocatalytic capabilities for environmental remediation to more expanded extent.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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