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# Full Length Article

# Growth regulation mechanism of nano-silica based on new ammonia-based $CO_2$ capture under external fields $\stackrel{\circ}{\approx}$



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# ABSTRACT

Conventional  $CO_2$  capture technologies often focus on the simple capture process, while the absorption and highvalue utilization of carbon capture products have profound significance, especially when combined with the utilization of biomass energy. Novel ammonia-based  $CO_2$  capture coupled with selective silicon dissolution was proposed with process regulation of external fields (i.e. magnetic field, microwave field, ultrasound field) used to prepare nano silica. The results show that the magnetic field plays a dual role of "vibration stirring" and adding energy (11.2 J/mol) on the formation and dispersion of nano silica. The specific surface area of nano-silica is increased from 140.24 m<sup>2</sup>/g to 280 m<sup>2</sup>/g by microwave field (250 W), and its "internal heating" promotes the formation of crystal nuclei. The ultrasonic field reduces the primary particle size of nano-silica by 3.17 nm, and inhibits the particle growth through cavitation and mechanical vibration. It would provide parameter support and optimization guidance for the low-cost high-quality nano silica for high-value utilization of ammonia-based  $CO_2$  capture products.

# 1. Introduction

Nano silica finds extensive application across diverse industrial sectors, including medicine, rubber, plastics, food, and more. owing to its superior qualities in adsorption and insulation (Ciriminna et al., 2013; Lei et al., 2020). Nonetheless, issues persist with elevated production expenses and limited distribution in practical applications (Huang et al., 2009; Jeelani et al., 2020). Addressing the issue of production costs could involve utilizing inexpensive raw materials like siliconrich biomass and integrating them with various industrial technologies to enhance economic and environmental advantages (Dorairaj et al., 2022). Biomass energy with CO<sub>2</sub> capture, utilization and storage technology (BECCUS) technology is a highly promising system that meets these conditions (Pang et al., 2023; Yang et al., 2022). This method yields significant environmental advantages by capturing CO<sub>2</sub>, and when integrated with nano silica production, it facilitates the efficient use of biomass (through chemical processes for biochar production and silicon dissolution) along with substantial economic gains (Zhang et al., 2017). Concurrently, creating nano silica offers a viable route for adsorbing the intermediate NH4HCO3 (NH3+H2O+CO2=NH4HCO3) in the ammonia carbon capture of BECCUS. Consequently, the integration of nano silica preparation and ammonia carbon capture techniques for joint production of "carbon silicon" represents a two-way promotional strategy. In order to provide sufficient silicon, rice husk (SiO<sub>2</sub> content  $\geq$  20 % (Shen and Zhang, 2019; Tabata et al., 2010)) has become the preferred raw material for connecting the environmental benefits of carbon capture and the economic benefits of nano silica preparation.

Co-producing "carbon silicon" can address nano silica's production expenses, and another issue, particle agglomeration, can be addressed through the preparation process. Widely used techniques for creating nano-silica encompass the gas-phase method (Pal et al., 2020), solgel method (Alvee et al., 2022; Singh et al., 2014), micro emulsion method (Cai et al., 2020; Da'na et al., 2022) and precipitation method (Awizar et al., 2013; Sarkar et al., 2017). While the gas-phase method yields high-purity nano-silica, it faces challenges like inadequate organic dispersion, complex post-treatment processes, and complex experimental conditions (Chen et al., 2019). The precipitation method has the advantages of easy access to raw materials and simple technology, and is a common preparation method for rice husk-based nano-silica (Thi Mai Anh et al., 2020). The majority of current studies enhance nano-silica's quality by managing process variables like concentration, temperature, dispersant, and activator (Li et al., 2019; Yang et al., 2021a). On the basis of pH regulation, CO2 and inorganic acids can be used as acidifying agents to prepare high-quality nano silica from rice husk (Liu et al., 2011; Zhao et al., 2020). Investigations into the workings of surfactant and dispersant remain unfinished, making it challenging to satisfy the

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requirements for particle size and dispersion in applications using a single agent or dispersant for control. In order to reduce the particle size of nano-silica and increase its dispersion, the mechanism of particle growth and powder agglomeration need to be further explored. The process of nano-silica agglomeration involves both hard and soft agglomeration due to van der Waals and Coulomb forces, removable through basic mechanical techniques. The formation mechanism of hard agglomeration is controversial, and the agglomeration of nano-silica is consistent with the agglomeration mechanism of most nanoparticles (Mulenos et al., 2020; Tabish et al., 2023; Wang et al., 2014). Therefore, it's beneficial to investigate the regulatory mechanisms of other nanoparticles, the introduction of various fields (such as magnetic, microwave, and ultrasonic) to enhance nano-silica dispersion. Anisotropy in the magnetic field influences how nanoparticles form and precipitate, thus controlling their growth process (Pol et al., 2006). Microwave-induced internal heating can accelerate the creation of nanoparticle nuclei and interfere with the van der Waals forces responsible for particle aggregation (Wen et al., 2013). The cavitation and mechanical shear phenomena of ultrasound can hinder crystal nuclei growth and enhance the dispersion (Wu et al., 2019). However, the effect and mechanism of external fields on the preparation of nano silica have not been thoroughly studied.

In this study, the carbon-silicon co-production technology has been proposed to solve the problem of product ( $NH_4HCO_3$ ) consumption in ammonia carbon capture method and create higher economic value. nano-silica is prepared by process regulation based on the reaction of  $NH_4HCO_3$  and  $K_2SiO_3$  (intermediate products) to solve the problems of equipment corrosion, low purity, low dispersion and large particle size. The intervention of external fields has mitigated the agglomeration of nano silica and the related mechanisms have been discussed. The research results can provide parameter support and optimization guidance for the development of low-cost, high-quality nano-silica preparation technology, and also provide key support for the improvement of ammonia carbon capture technology system.

#### 2. Material and methods

#### 2.1. Materials

The rice husk for the preparation of nano-silica is from Wuchang City, Heilongjiang Province. The primary chemical reactions involved in the production of rice husk biochar through KOH chemical activation (Fu et al., 2018; Guo et al., 2022) include: 2KOH+ Pyrolysis biochar(SiO<sub>2</sub>) $\rightarrow$ Quality biochar+K<sub>2</sub>SiO<sub>3</sub>+H<sub>2</sub>O, K<sub>2</sub>CO<sub>3</sub>+ Pyrolysis biochar(SiO<sub>2</sub>) $\rightarrow$ Quality biochar+K<sub>2</sub>SiO<sub>3</sub>+CO<sub>2</sub>,selective silicon dissolution product K<sub>2</sub>SiO<sub>3</sub> is selected as a silicon source for the preparation of nano-silica (Fig. 1(A)). The origin of the carbon source can be traced back to NH<sub>4</sub>HCO<sub>3</sub> (Fig. 1(A)), which is the outcome of the innovative ammonia capture technique. The main chemical reaction is:  $2NH_4HCO_3+K_2SiO_3\rightarrow 2NH_3\uparrow+H_2O+SiO_2\downarrow+2KHCO_3$ , as shown in Fig. 1(B). While *Table S1* displays the information on all reagents utilized in the preparation and characterization procedure. In addition, the specific steps of the silicon dissolution method can also be seen in the supporting documents.

#### 2.2. Experimental process for preparation of nano-silica

The experimental systems (equipment) used in this study encompass a system for generating magnetic fields and a versatile microwave extractor with access to both microwave and ultrasonic fields, as detailed in the supporting document (*Figure S1~S2* and related text).

The  $K_2SiO_3$  solution, a product of silicon dissolution, was combined with identical quantities of ultra-pure water, a dispersant (15 % anhydrous ethanol), and a surfactant (PEG 6000, 0.18 g/50 mL). After dissolving NH<sub>4</sub>HCO<sub>3</sub> crystals, the K<sub>2</sub>SiO<sub>3</sub> solution was transferred into the NH<sub>4</sub>HCO<sub>3</sub> solution, then immersed in a water bath, stirred heated for 1

Table 1

Experimental condition and sample desc	ription.
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Treatment	Field
Water bath	-
0.3 $T$ +Water bath	Magnetic field
0.3 T +Room temperature	Magnetic field
0.5 $T$ +Water bath	Magnetic field
0.5 T +Room temperature	Magnetic field
1.0 T +Room temperature	Magnetic field
250 W +Microwave heating	Microwave field
300 W + Microwave heating	Microwave field
400 W + Microwave heating	Microwave field
400 W + Microwave heating	Ultrasonic field
600 W + Microwave heating	Ultrasonic field
800 W +Microwave heating	Ultrasonic field
	Treatment Water bath 0.3 T +Water bath 0.3 T +Room temperature 0.5 T +Room temperature 1.0 T +Room temperature 250 W +Microwave heating 300 W +Microwave heating 400 W +Microwave heating 600 W +Microwave heating 800 W +Microwave heating

hour, and aged for 3 h. The sample was then washed and freeze-dried to produce nano-silica products, which were recorded as S0.

On the above experiment basis, field experiments are carried out. **Magnetic field experiment:** The magnetic field intensities are set at 0.3 T, 0.5 T, 1.0 T (subject to experimental conditions, no water bath heating under 1.0 T) and the corresponding sample numbers are S1-M ~ S5-M. The reaction solution is placed in the quartz reactor with a circulating water bath heating function (*Fig. S1*), and then in the middle of a magnetic field generator. *Microwave field experiment:* The nano-silica samples are recorded as S6-W, S7-W, and S8-W with different microwave power (250 W, 300 W, and 400 W) representing microwave field strength. *Ultrasound field experiment:* Ultrasonic powers are selected at 400 W, 600 W, and 800 W, corresponding to nano-silica numbers S9-U, S10-U, and S11-U, respectively. The reaction reagents are placed in a dedicated multi necked flask (*Fig. S2*) for microwave/ultrasonic treatment. Specific experimental conditions are shown in Table 1, and the experimental processes are shown in Fig. 1(C).

## 2.3. Analytical methods

The physicochemical characterizations used in this study include XRD, specific surface area test, DBP Oil absorption test and HRTEM. Dibutyl phthalate is used as a test agent to determine the oil absorption value of nano-silica based on the manual testing method in *HGT* 3072–1999 (details can be found in supporting document). Oil absorption value is the volume of dibutyl phthalate absorbed, which can reflect the pore volume and concentration of nano-silica. Specific test information can be seen in the supporting document.

#### 3. Result and discussion

#### 3.1. Characterization of original nano-silica

The preparation of nano-silica is regulated by selecting reaction reagents and freezing method. The characterization results and related mechanisms are shown in Fig. 2. The XRD spectrum of S0 is shown in Fig. 2(A), and there is only a slow peak at  $2\theta = 22^{\circ}$ , with no other heterozygous peak, indicating that the product under initial conditions is typically amorphous SiO<sub>2</sub> (Ke et al., 2020; Mulenos et al., 2020; Yang et al., 2021b) and has a high purity. The specific surface area and oil absorption value of S0 are given in Fig. 2(B).

The average particle size and morphology of nano-silica are obtained by TEM characterization (Fig. 2(B)). Initially, the primary particle size of the nano-silica is 13.60 nm (less than 100 nm), meaning the fundamental conditions for nano-silica production are satisfied through the freezedrying method with water bath, choosing polyethylene glycol 6000 as surfactant and anhydrous ethanol as dispersant.

As can be seen from Fig. 2(B), although S0 has reached nanoscale, there is still a significant agglomeration. Aggregation is caused by the special structure of nano-silica (SiO<sub>2</sub>  $nH_2O$ ), in which  $H_2O$  molecules



**Fig. 1.** Preparation principle and process of nano-silica (A) Physical image of  $NH_4HCO_3$  preparation (B) Schematic diagram of the principle for preparing nano silica (C) Experimental process for preparing nano silica under external field conditions.

are present in the form of -OH groups. These groups are composed of separated hydroxyl groups, isolated hydroxyl groups, and adjacent hydroxyl groups, as shown in Fig. S3. Hydroxyl groups easily bond with water, creating hydrogen bonds that enhance the surface activity of nano-silica particles and promote the agglomeration of SiO<sub>2</sub> with smaller primary particles. The mechanical effect does not completely eliminate agglomeration of S0, which means that there is a hard agglomeration, and besides Coulomb and Vander Waal forces which are easily eliminated, there are also chemical bonds which are not easily eliminated. To manage and eradicate the hard agglomeration of nano-silica through nanoparticle hard agglomeration mechanisms (Ognjanovic and Winterer, 2018; Stauch et al., 2017; Wintzheimer et al., 2019), four key strategies are employed: (1) Preventing the production of surface hydroxyl groups; (2) Avoiding the interaction of the surface hydroxyl layer between adjacent particles; (3) Reducing or eliminating the active surface hydroxyl layer; (4) Increasing the spatial distance between particles and decreasing the interaction of surface hydroxyl layer. These are also the basis of process regulation in this study.

The mechanism of surfactant PEG 6000 is shown in Fig. 2(C),(D): PEG 6000(H (OCH<sub>2</sub>CH<sub>2</sub>)nOH) with the hydrophilic group  $-CH_2CH_2$ and the hydrophilic group -OH dissolve in water and form a zigzag structure (Fig. 2(C)), coated with hydrogen bonds on the surface of silica nanoparticles (Sun et al., 1999), thus producing interfacial films to increase the spatial distance between particles and reduce the interfacial energy of particles to OH-ions (Sun et al., 2000), inhibiting the interaction of adjacent hydroxyl layers. The dispersant anhydrous ethanol can be used to maintain the concentration of the reaction solution, improve the reaction rate and reduce particle agglomeration. Since the amount of surfactant and dispersant is difficult to control and match with the reaction material, it is difficult to achieve the desired dispersion effect through single surfactant/dispersant regulation. Vacuum freeze-drying is used instead of high temperature drying, and solvents are quickly frozen to form "solid bridges" between particles rather than "liquid bridges" during heat drying. *In-situ* sublimation induced by increased vacuity eliminates the particle compression effect of heat drying, effectively preventing secondary aggregation, as shown in Fig. 2(E).

The specific surface area of  $140.24 \text{ m}^2/\text{g}$  is determined by nitrogen adsorption, meeting only the Class C standard for rubber nano-silica, whose specific surface area (sum of the external surface area and internal surface area) is influenced by factors such as the size of the primary particle size and polymerization method. The absorbent reagent is dibutyl phthalate, which is a large molecule, so the absorption value of oil depends mainly on surface area, with an absorption value of 3.16 mL/g for S0. The external surface area of nano-silica particles is larger than the internal surface area, so the oil absorption value is high. By synthesizing the specific surface area, oil absorption value and TEM images of the initial product, it can be concluded that the traditional modification methods such as surfactant, dispersant and freeze-drying can only form nano-silica, and the dispersion improvement is not great,



Fig. 2. Nano-silica process regulation (A) Nano-silica XRD spectrum (B) TEM results of S0 (C) Hydration state of PEG-6000 (D) Coating schematics of PEG-6000 (E) Vacuum freeze-drying principle.

and the specific surface area can only reach the standard of the national standard C.

#### 3.2. Effect and mechanism of magnetic field regulation

Table S2 and Fig. 3(A) show the specific surface area and oil adsorption value of samples under different field strength and water bath conditions. As shown in Fig. 3(A), the specific surface area of nano-silica increases significantly with the increase of magnetic field strength under water bath heating conditions. When the magnetic field strength is increased to 0.5 T, the specific surface area of S3-M reaches 307.80 m<sup>2</sup>/g, meeting the Class A standard for rubber nano-silica products, while the oil adsorption value is 3.13 mL/g, lower than that of S0, suggesting that the application of magnetic fields during the reaction can effectively increase the internal surface area of nano-silica products rather than their external surface area, as shown in Fig. 3(B).Comparing S3-M and S4-M, it is found that water bath heating can improve the specific surface area and oil absorption value of nano-silica. When the magnetic field strength is 1.0 T, the specific surface area reaches 260.94  $m^2/g$  without water bath heating, meeting the Class A standard for rubber nano-silica. In summary, both magnetic field and water bath heating can improve the quality of nano-silica.

Water bath temperature affects the polymerization (nucleation) of nano-silica particles. When the reaction temperature is too low, the nucleation process reacts more slowly because the viscosity of the dripping  $K_2SiO_3$  solution increases, leading to less collisions between particles. The larger clusters are less dynamic, and the aggregation process is mainly caused by collisions between small particles or clusters, resulting in tight and solid clusters. Conversely, as the temperature increases, the viscosity of the dripping  $K_2SiO_3$  solution decreases, collisions between particles intensify, and the reaction speed accelerates. Large clusters are more dynamic, and clustering occurs between large clusters and individual small particles, or between large clusters and small clusters. At the same time, rising temperature favors the role of surfactants, offsetting some effects of the rapid growth of particles. However, excessive reaction temperature can also increase the growth and nucleation rate of particles (Zhang et al., 2021), leading to larger primary particle sizes of nanoparticles of silica, and excessive reaction temperature can also lead to rapid decomposition of  $\rm NH_4HCO_3$  solutions, affecting reactant concentrations. Water bath heating at appropriate temperature is a necessary condition to improve the quality of nano-silica.

To further investigate the effects of magnetic fields and bath temperatures on nano-silica products, some nano-silica products are tested with HRTEM, as shown in Fig. 3.Under other invariable conditions, when a magnetic field of 0.3 T is applied during the reaction process, the accumulation of nano-silica powders is significantly reduced, and the average particle size is reduced from 13.60 nm to 10.28 nm, demonstrating that the magnetic field positively contributes to the formation and dispersion of nanoparticles. As shown in Fig. 3(D), in the presence of magnetic fields but without water bath, the nano-silica product has a significant increase in the primary particle size to 97.67 nm, while stacking and agglomeration are not significant. The results indicate that reaction temperature directly influences the growth of primary particles and magnetic field influences the further agglomeration of nanoparticles. When the magnetic field intensity increases to 1.0 T (Fig. 3(E)), the average particle size is 14.94 nm and nanoparticle accumulation is significantly reduced. The magnetic field also eliminates some of the problems associated with primary particle size growth due to the absence of a water bath. According to the experimental results and literature (Katiyar et al., 2015; Shasha and Krishnan, 2021), the magnetic field applied in the process of preparing nano-silica by sedimentation is more in line with classical mechanics theory and thermodynamics theory, and plays a dual role of vibration agitation and adding energy to the system. When the magnetic field strength rises to 1.0 T, not only does the accumulation decrease, but so does the primary particle size increase due to the absence of water bath. It can be argued that when a strong magnetic field is applied, the increased reaction rate due to sufficient energy offsets the decreased reaction rate due to lower temperature.

#### 3.3. Effect and mechanism of microwave field regulation

Microwave is applied during the reaction to increase the reaction temperature and the HRTEM photo of nano-silica is shown in Fig. 4(A). The primary particle size of S8-W is only 7.73 nm, which is



Fig. 3. Effect of magnetic field strength on nano-silica (A) Trends in specific surface area of nano-silica with magnetic field intensity (B) Diffusion of magnetic field to nano-silica (C) TEM characterization of S1-M, S2-M and S5-M (D) size distribution of S1-M, S2-M and S5-M.

5.87 nm lower than that of S0 sample, and the stacking of nano-silica particles is reduced. Nano-silica products prepared under microwave environment are characterized for BET specific surface area and oil absorption value, and the results are shown in *Table S3*. The specific surface area of the microwave treated nano silica products is about 280 m<sup>2</sup>/g, and the oil absorption value is about 3.30 mL/g, which can meet the Class A standard of nano silica for rubber. Compared with the S0 sample, the specific surface area is significantly increased, from 140.24 m<sup>2</sup>/g to 280 m<sup>2</sup>/g. As the temperature and power of the microwave heating system form feedback, when the set temperature is unchanged, simply increasing the maximum power will not lead to significant changes in the actual power (*Fig. S4*), so the increased maximum microwave power does not lead to the promotion effect on the specific surface area and oil absorption value.

According to the above results, the application of microwave field has obvious effects on the size reduction and specific surface area increase of nanoparticles. As shown in Fig. 4(B), in the traditional heating process, the heat transfer form is heat conduction, and the heat is transferred from the container to the outside liquid and then to the inside liquid, forming "cold centers". When  $K_2SiO_3$  solution is dropped in, the rate of temperature rise is far lower than the rate of reaction, resulting in that the temperature. The viscosity of the dropped  $K_2SiO_3$  is large, and the reaction rate is not fast enough, leading to the tendency of the product to compact and solid aggregates. Therefore, the nano-silica particles prepared under the condition of only water bath heating have larger primary particle size and smaller specific surface area. In fact, microwave heating realizes heat transfer by thermal radiation, allowing molecules, atoms or ions in the reaction system to obtain energy by absorbing microwave radiation, which will not produce large temperature gradients and avoid "cold centers". When  $K_2SiO_3$  solution is dropped, microwave radiation will rapidly increase the internal temperature of the solution, speed up the reaction rate, and rapidly form a large number of crystal nuclei, which will reduce the particle size of nano-silica. Microwave heating can not only accelerate the reaction rate by promoting the collision between particles through "internal heating", but also improve the reaction rate by increasing the active entropy of reactants, which will accelerate the reaction fracted by order of magnitude.

#### 3.4. Effect and mechanism of ultrasonic field regulation

Based on the microwave conditions, the mechanism of the influence of ultrasonic field on the growth process of nano-silica particles is investigated. Fig. 5(A) shows the TEM characterization results of S11-U. When the ultrasonic power is 800 W, the primary particle size is reduced from 13.60 nm to 4.56 nm compared with S0, and the particle size is also reduced from 7.73 nm to 4.56 nm compared with the product only applied with microwave. Although the primary particle size of nano-silica is reduced, the addition of ultrasonic field on the basis of microwave field will increase the stacking of nano particles. Although the addition of ultrasonic wave will significantly reduce the primary particle size of nano-silica, the dispersion degree has not been improved. **Table** 



Fig. 4. Effect of microwave field on nano-silica (A) TEM characterization results of S8-W (B) Action mechanism of microwave field.

(A)



Fig. 5. Effect of ultrasonic field on nano-silica (A) TEM characterization results of SU-11 (B) Schematic diagram of action mechanism of ultrasonic field.

S4 shows the BET specific surface area and oil absorption value of S9-U, S10-U and S11-U. When the ultrasonic power is increased from 400 W to 600 W and 800 W, the specific surface area value decreases instead, and the oil absorption value also decreases slightly. As shown in Fig. 5(A), when the power is increased to 800 W, the dispersion is not satisfactory. The reason may be that the ultrasonic power is too high and the particle growth rate becomes faster during the nucleation stage, which leads to the excess energy used for further stacking and agglomeration of primary particles, resulting in obvious stacking of nano-silica particles, and the specific surface area value decreases from 308.25 m<sup>2</sup>/g to 179.06 m<sup>2</sup>/g, but still higher than S0.

Applying ultrasonic field will play three roles in the reaction process: (1) Nucleation is completed with the help of ultrasonic energy; (2) High temperature decomposition by cavitation. Cavitation refers to the generation of a large number of tiny bubbles under the ultrasonic wave, which will grow up and break again. The shock wave generated at the moment of breaking can act on the particle surface (Wu et al., 2019); (3) The primary particle size is controlled by shear fragmentation mechanism. Ultrasonic wave plays a role in the three stages of the formation of nano-silica particles. In the initial stage of crystallization, ultrasonic wave continues to provide sufficient energy for the particles to be nucleated in the solution to promote the formation of crystal nuclei; In the nucleation stage, the ultrasonic energy will further promote the primary particle size growth of the crystal, providing energy for the non nucleated particles; During the growing stage, the cavitation and mechanical vibration of ultrasonic wave will prevent the particles from growing further. The nano silica product thus obtained has small particle size and relatively good dispersion. The schematic diagram of ultrasonic mechanism is shown in Fig. 5(B).

#### 4. Conclusions

- (1) Nano silica with specific surface area of  $140.24m^2/g$  and oil absorption value of 3.16 mL/g was prepared by converting silicon dissolving product  $K_2SiO_3$  and ammonia carbon capture product  $NH_4HCO_3$  through precipitation method.
- (2) The magnetic field with a dual role of "vibration stirring" and additional energy can cause a positive effect on the formation and dispersion of nano silica, and it is more conducive to increasing the internal surface area of nano-silica. When the magnetic field strength is increased to 1.0 T, the average particle size is 14.94 nm, and the stacking phenomenon is significantly reduced.
- (3) The specific surface area of the microwave treated nano-silica increases from  $140.24 \text{ m}^2/\text{g}$  to  $280 \text{ m}^2/\text{g}$ , and the oil absorption value is determined to be about 3.30 mL/g, which can meet the Class A standard of nano-silica for rubber. The "internal heating" of microwave field can promote the formation of crystal nucleus and reduce the active entropy of reactants.
- (4) Ultrasonic field can increase the specific surface area of nanosilica. When the power is high (800 W), the primary particle size decreases from 7.73 nm to 4.56 nm, but the specific surface area decreases. The action mechanism of ultrasound is to provide energy and restrain particle growth through cavitation and mechanical vibration.

### **Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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# Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ccst.2024.100205.

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