A Comprehensive Review of Synthesis, Applications and Future Prospects for Silica Nanoparticles (SNPs)

Faheem Akhter1 · Ahsan Atta Rao1 · Mahmood Nabi Abbasi1 · Shafeeqe Ahmed Wahocho1 · Mukhtiar Ali Mallah1 · Hafiz Anees-ur-Rehman1 · Zubair Ahmed Chandio1

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Abstract
Silica nanoparticles (SNPs) have shown great applicability potential in a number of fields like chemical, biomedical, biotechnology, agriculture, environmental remediation and even wastewater purification. With remarkably instinctive properties like mesoporous structure, high surface area, tunable pore size/diameter, biocompatibility, modifiability and polymeric hybridizability, the SNPs are growing in their applicable potential even further. These particles are shown to be non-toxic in nature, hence safe to be used in biomedical research. Moreover, the molecular mobilizability onto the internal and external surface of the particles makes them excellent carriers for biotic and non-biotic compounds. In this respect, the present study comprehensively reviews the most important and recent applications of SNPs in a number of fields along with synthetic approaches. Moreover, despite versatile contributions, the applicable potential of SNPs is still a tip of the iceberg waiting to be exploited more, hence, the last section of the review presents the future prospects containing only few of the many gaps/research extensions regarding SNPs that need to be addressed in future work.

Keywords Silica nanoparticles · Mesoporous · Nanotechnology · Nanostructure

1 Introduction

Nanotechnology deals with development of unique nanoscale particles. These particles have found revolutionizing applications in various industries like electronics, medicine and consumer products. In recent years, one such example of nanotechnology are silica nanoparticles that have found a widespread use in industrial, food and agricultural fields. Generally, the nanoparticles are synthesized via physical and chemical methods. The physical methods include ultrasonic shot peeling, severe plastic deformation, gas condensation, high energy ball milling and pyrolysis [1]. These techniques usually are employed to synthesize metallic nanoparticles. On the other hand, Chemical methods include electrochemical procedures, reduction of chemicals/phytochemicals, chemical coprecipitation, chemical vapor condensation and pulse electrodeposition [2–4]. In comparison, the chemical methods involve the use of various toxic and hazardous chemicals that are harmful for the biosphere and environment. This paved the way for the development of green nanotechnology that uses environment friendly methods and bio-agents to synthesize nanoparticles. In general, the green nanotechnology uses microorganism (fungi, bacteria, algae) and nature derived substrates (plant extracts) to synthesize nanoparticles. Besides being eco-friendly, these methods are comparably inexpensive too [4, 5]. Silica nanoparticles are usually synthesized from alcohol solution of silicon alkoxides. Ammonia is used as a catalyst and the
nanoparticles can range from 50 nm – 1μm, depending upon the versatile applications.

Metal oxides play a significant role in many areas of nano-material science. In any material, the particle size determines its structure, size and other properties that are affected by the size of oxide particles. For example, the chemical reactivity and conductivity of metal oxide are significantly influenced by the size of an oxide particle [6, 7]. Similarly, the surface properties are equally important due to their huge role during solid-liquid or solid-gas reactions [8]. Numerous metal nano-particles have been synthesized such as ZrO₂, CeO₂, TiO₂, TiO₂ etc. which can be exploited for applications such as sensors, coatings, agrochemicals, anti-corrosives, fuel cells and catalysts [9, 10]. For example, the NPs of iron oxide carry a strong magnetic characteristics, hence are used for the relevant applications such as separation of cells parts, drug delivery, nano-coating and food packaging [11–13].

Silica is one of the most abundant materials on earth [14]. Silica nanoparticles (SNPs) have gravitated much of the recognition by the research world due to their diverse physiochemical properties [15]. Based on the pore size, these particles can be divided into mesoporous and nanoporous [16]. The size of the particles can be varied by altering the surfactants’ composition during synthesis [17]. Silica nanoparticles (SNPs) are usually inexpensive to produce on a large scale, are hydrophobic with good surface area, pore volume and biocompatibility, hence they have found wide variety of applications. For example, due to their non-toxic nature and fantastic adsorption capacity, the silica nanoparticles (SNPs) have been employed for drug delivery [18, 19]. Recently, the researchers have successfully utilized the silica nanoparticles (SNPs) as loading multifarious for cargo ranging from drugs to macromolecules, such as RNA, DNA and proteins [20, 21]. So far, the silica nanoparticles have found applications in numerous directions of research such as biomedicine, biotechnology, drug delivery, food, personal care products, pesticides, adsorption, semiconductors and ceramics [22]. More recently, the silica nanoparticles have been employed to adsorb the oil spillage during oil exploration, transportation and storage [23, 24]. The research is still in the progress to explore and exploit more possible applications of silica nanoparticles [22].

2 Synthesis of Silica Nanoparticles (SNPs)

2.1 Synthesis of SNPs (Chemical Methods)

In the past, silica nanoparticles were synthesized using classical methods like sol-gel method, stober’s method, flame synthesis and micro emulsion [17]. These chemical routes are easy to follow and modify in terms of parameters but can be costly and difficult to manage. For example, during reverse micro emulsion, the surfactant molecules are dissolved in the presence of water which produce the spherical micelles. Although this procedure is effective, yet it is costly and difficult to segregate the surfactants in the final products [16]. Nevertheless, the nanoparticles synthesized via this route were successfully used as coating to attach functional groups [25, 26].

Another popular route to synthesize silica nanoparticles is chemical vapour condensation (CVC) [27]. During this method, silicon tetrachloride is reacted with oxygen and hydrogen. The physical aspects of the nanoparticles such as morphology and particle size can be controlled to the desired characteristics in this process. This method is widely used to produce nanoparticles in powder form [28–30]. Similarly, the sol-gel method is a well known technique used widely to synthesize silica and silica gel [31, 32]. It mainly involves the hydrolysis and condensation of metal alkoxides like TEOS or inorganic salts like sodium silicate in the presence of a catalyst. The catalyst being acid or base [33, 34]. When forming silica particles using metal alkoxides (TEOS, TMOS), the hydrolysis gives silanol groups that polymerize to form into silica structure. Another method called stober’s method was first experimented and proposed by Werner Stober. Using ammonia as a catalyst, he successfully synthesized spherical silica particles from silica alkoxide alcohol solution. The particle size ranged from 5 to 2000 nm [35]. This method has evolved with time and made much more efficient and versatile in terms of controlling parameters and acquiring the desired properties [36, 37]. Usually, the acid catalyzed systems produce gel structure whereas the Stober’s method gives monodispersed silica particles [35]. Despite its own advantages, the chemical synthesis methods are expensive, involve toxic substances and require high energy, which necessitated the birth of biogenic routes [22]. Figure 1 schematically represents the most commonly used chemical techniques to synthesize silica nanoparticles.

2.2 Synthesis of SNPs (Biogenic Methods)

The biogenic methods of synthesizing silica nanoparticles involve using microorganisms and nature derived substrates, such as bacteria, fungi, algae and plant extracts/metabolites [38]. For example, the biosilicification process produces silica via silicatein and silaffin, which has led to the designing of synthetic cationic polypeptides. Moreover, the usability of fungus for silica synthesis had been investigated by many researchers. For example, the fungus Fusarium oxysporum was reacted with aqueous anionic complex at room temperature to form silica [39, 40]. Recently, various biomass have been investigated to synthesize silica nanoparticles, like rice husk, sugarcane bagasse and rice straw [14, 41–44]. Silica present in the biomass is initially isolated and formed into
sodium silicate solution [45]. Number of parameters affecting the process that need to be optimized like temperature, pH and time [46]. Such a step is an appreciative way to deal with the biomass and convert it into valuable products like silica nanoparticles that are gaining wider applications with time [47].

In order to synthesize silica, the biomass is usually washed with distilled water to remove adhering impurities followed by treatment with leaching agents [48]. The leaching treatment is aimed to remove the metallic impurities contained by the biomass [49]. Table 1 shows the most common metallic impurities in rice husk and their removal via different acids. If not removed, these metallic impurities can downgrade the physiochemical properties of the obtained silica particles [41]. In this regard, 3 acids are most commonly used; hydrochloric acid, nitric acid and sulfuric acid. Among them, the HCl is known to

| Constituent (%) | Non-Leached Rice Husk Ash at 600 °C | Acid Leached Rice Husk Ash at 600 °C |
|-----------------|-------------------------------------|--------------------------------------|
| SiO₂            | 95.77                               | 99.58                                |
| Al₂O₃           | 0.05                                | 0.02                                 |
| FeO₃            | 0.05                                | 0.03                                 |
| CaO             | 0.67                                | 0.04                                 |
| MgO             | 0.40                                | 0.02                                 |
| Cl              | 0.02                                | 0.02                                 |
| SO₄             | 0.62                                | 0.02                                 |
| K₂O₂            | 0.62                                | 0.02                                 |
| Na₂O            | 1.26                                | –                                    |
| P₂O₅            | 0.46                                | 0.11                                 |
remove 99% of the metallic impurities [49–53]. Base and salt treatment is also investigated to remove the impurities, such as sodium hydroxide and KMnO₄ [54].

This leaching pre-treatment is followed by calcination of biomass. Synthesis of high purity silica highly depends on temperature, time and air/oxygen flow [56]. For example, in case of rice husk, the silica obtained at 600 degrees was amorphous in nature while at 700 was both amorphous and crystalline. Higher temperature than 700 is shown to produce more crystalline structure of rice husk than amorphous [57–60].

Various researchers used green synthesis route to obtain amorphous silica nanoparticles (SNPs) using rice husk and sugar beet bagasse [22]. The researchers who used rice husk successfully obtained semi-crystalline porous silica nanoparticles and silica nanoparticles [29, 61]. On the other hand, the researchers who used sugar beet bagasse also synthesized silica nanoparticles [62]. Figure 2 shows the classified chemical and biogenic routes to synthesize silica nanoparticles (SNPs).

3 Applications of Silica Nanoparticles (SNPs)

3.1 Chemical Applications of SNPs

Silica nanoparticles possess specific sites that make it easy for the particles to get functionalized. For example, the mesoporous silica nanoparticles (MSNs) contains 3 major sites for functionalization; pore walls, pore entrance and interior/exterior of the particle surface [16, 63]. Figure 3 shows the mechanism for MSNs formation.

Silica particles are usually functionalized via co-condensation or post synthesis grafting using organo-substitutedtrialkoxy silanes [17]. When functionalized on to the pore walls, the mesopores do not get blocked by non-siliceous group. During functionalization, the alkoxy silanes bind to the surface silanol groups. Similarly, numerous metals have also been functionalized onto the mesoporous silica particles [65, 66]. For example, Aluminum is one of the most common metals functionalized on to MSNs for catalytic related applications. In this regard, Zhai et al. [67] synthesized aluminosilicate nanoparticles. Moreover, the particles were mesoporous and the particle size was limited to 20 nm by using polyethylene glycol. Similarly, Zhao et al. [68] synthesized magnetic MSNs using hermatite nanocore. The
When it comes to biomedical, the research of drug delivery carries one of the highlighting importance. Using the engineered nanostructures for the targeted delivery of drugs in the patient’s body is a significantly recognized feature under research [76]. These nanostructures can act as carriers and target specific organs or tissues in the body. In this regard, MSNs have achieved significant recognition due to their high surface area and porous structure. These particles have been used as nano-carriers for drug delivery in recent times [18, 20, 22, 77–79]. Auggenhaug et al. [80] investigated the release of drug using silica xerogels as potential carriers. Moreover, the hydrophobicity of the drugs reduces their absorption during oral dose. This is improved by using SNPs as carriers for such hydrophobic drugs and shown promising results during oral doses [76]. It is possible due to the negative charge on the surface of silica nanoparticles whereas positive on hydrophobic drug [28]. Furthermore, what makes these nanoparticles so efficient are their loading capacity, biocompatibility and possible functional group modification [16]. In this, Zhang et al. [81] used SNPs as carriers for hydrophobic drug telmisartan. The SNPs were shown to improve the drug permeability. Likewise, Samira et al. [82] and Nihal et al. [83] showed a significant improvement in the functionality of curcumin (anticancer drug) conjugated with SNPs than used alone. Lein et al. [84] synthesized nanoparticles for controlled drug delivery by successfully grafting magnetic and thermosensitive nanoparticles onto the surface of Fe3O4 coated silica particles. Similarly, the surface modified SNPs have been investigated for boron neutron capture [85–89].

Having large surface area and small size, the SNPs have found their applicability as biomarkers to detect specific biomolecules. In this regard, the use of Quantum Dots (QD) is widespread, however their insolubility in water and toxicity caused by heavy metals have provoked researchers to find alternate substitutes. In this respect, various researchers covalently linked the compounds; such as fluorophores and tetramethyl rhodamine isothiocyanate dye, onto the silica nanoparticles. The fabricated materials showed water soluble and less/non-toxic conduct with promising results, hence a worthy substitute for QDs [90–94]. Moreover, the adhesive properties of SNPs have been utilized by researchers to synthesize glue like material, which is shown to be less invasive compared to commonly used tissue adhesives like cyanoacrylate [22]. Another remarkable property owned by SNPs is their differentiation of cells, which has been proposed as a treatment for obesity [19, 95]. Flourine Nucleus (19F) is very sensitive and present in traces of biological tissues, hence used to detect even the very minute details. However, it is challenging to develop fluorine containing probes for 19F MRI. This scenario has led to the grafting of fluorine onto the silica nanoparticles, which can be immobilized on the inner as well as outer layers of the particles [96–99].

Medical diagnosis and research have to interact and detect very minute targets like proteins, enzymes, DNA and mRNA, hence requiring a very precise and specific detection. In this respect, the nanotechnological developments are showing to be a supportive and contributive factor in medical research [100]. Nanotechnology has already shown promising results in drug delivery, diagnosis, medical imaging, cancer treatment, diabetes treatment and more [19, 61, 79]. SNPs have shown to be good adsorption and immobilization medium for quinizarin diester [101]. Maleki et al. [102] developed drug delivery system using silica nanoparticles. They further showed the possible feasibility of using the same system for entrapment of colorless water soluble drugs like isoniazid. Following the same track, various researchers in recent time have explored more water soluble drugs that were successfully immobilized onto the silica nanoparticles and used for drug delivery [103–107]. For example, Marzieh et al. [108] developed silica based nanocarriers for the target...
delivery of doxorubicin drug to breast cancer cells (4T1). The nanocarriers were fabricated with quantum dots (QD) coating on MSNs followed by amine functionalization of silica surface. The drug was into the silica pores and biheterofunctional PEG was covalently bound to the surface of core-shell QDMSNs. The results were remarkably positive. Figure 4 shows the SEM images of the synthesized nanoparticles (QDMSNs, PEG QDMSNs, HRTEM and QDNPs).

Antibiotics have been a major development of medical research. However, these drugs come with its own challenges like depletion of their antibacterial effect with time and release of toxic substances into the environment [71]. On the contrary, various compounds have been synthesized as antibacterial agents that kill bacteria on contact, such as quaternary ammonium compound [109]. These antibacterial agents have been cross-linked to SNPs to develop particles with chemically inert nature, transparent and good mechanical properties [6, 110]. One of the issues related to development of latest antibiotics are their toxicity and low bacterial penetration. To address these issues, SNPs were used to encapsulate peptide, which showed to be effective in treating lung infection (Pseudomonas aeruginosa). The SNPs being biodegradable, ensured target release of peptide [111]. Similarly, the treatment of diseases like tuberculosis carries its own set of challenges that need to be overcome. For example, well known drug called clofazimine is shown to have poor solubility and adsorption in GI tract. To overcome this, the researchers [112] encapsulated this drug onto SNPs, thus resulting in its enhanced stability and solubility. In short, the SNPs can be a reliable support for immobilization and encapsulation of antibacterial agents/drugs in future with minimum/less toxicity [18, 53].

### 3.3 Agricultural Applications of SNPs

Higher agricultural production ensures the survival of the growing population in the world. Unfortunately, microbial and insect attacks can significantly reduce this yield. This issue is being resolved by using pesticides but their health and environmental concerns have led to even worse problems. The excessive use of pesticides is not only harmful for the soil, but also for human health and environment. The direct shower of pesticides onto the crops might get absorbed and become intact within the crops, consequently, ending up in the human bodies and giving way to numerous diseases like respiratory symptoms, neurological problems, hormonal, reproductive abnormalities and even cancer [113]. This has provoked the researchers to synthesize an eco-friendly insecticides. Furthermore, another approach to do away with the pesticides is to strengthen the immunity of seeds against microbial attacks. This has been possible using MSNs [114, 115]. For example, Torney et al. [116]...
loaded MSNs with genetic material and chemical inducer to be successfully carried into intact leaves and plant cells of maize seeds. This pre-treatment of maize seeds with silica nanoparticles resulted in maize seeds with antifungal resistance, higher nutritional content and greater germination rate. Similarly, Siddiqui et al. [117] were able to achieve 22.16% higher germination rate by using 8g/L of SNPs. This shows the impact of silica nanoparticle concentration on germination rate. Furthermore, the recent research by Maryam et al. [118] is worth mentioning, where the researchers developed poly-ethyleneimine (PEI) coated MSNs. The particles were loaded with genetic material (pDNA) for an efficient and successful transfection to plant cells via ultrasonic treatment. Figure 5 reflects the genetic adsorption capacity of PEI-MSNs for DNA.

It is very difficult for the plants to survive during the stress conditions like salinity. This can be resolved by encoding the protein with the gene so that the plant develops more tolerance to the critical conditions of salinity. However, this process is very expensive and time consuming. Hence, the researchers have shown the possibility of loading the gene onto the silica nanoparticles. For example, Kalteh et al. [119] used SNPs on Basil plants with an increased saline conditions. The SNPs were shown to reduce sodium toxicity and enhance the stress tolerance in the plants. On the other hand, another research [120] treated algae (Scenedesmus obliquus) with SNPs. Contrary to the preceding research, it was shown that the higher SNPs concentration reduced the chlorophyl content of the algae. However, good stress tolerance was observed at moderate concentration of SNPs. It can be stated that overall, the use of silica nanoparticles strengthens the plants, enhances their stress tolerance and is non-hazardous Table 2.

### 3.4 Applications of SNPs in Food Preservation

Besides various other applications, the SNPs have also found their contributive role in food preservation. In this, numerous fruits can be coated with silica based hybrid films to increase their shelf life, hence preserve for longer periods of time [127]. This novel approach has been explored and confirmed by various researchers. For example, Mirzadeh et al. [128] synthesized a hybrid composite film of chitosan and nano-silica. The film was coated onto the Longan fruits and was shown to significantly enhance their shelf life. Also, the film reduced the weight loss and browning effect of the fruits. Similarly, another research [129] used the same hybrid film coating on Loquat and observed enhanced shelf life, improved enzymatic activity and increased levels of reducing sugars. Figure 6 shows the synthetic scheme of Chitosan/Silica hybrid composite film for Loquat fruit preservation.

Moreover, the simple process to synthesize silica based hybrid films have attracted the focus of researchers worldwide and provoked to exploit for more applications. Similar, the hybrid composites made with silicates and polymers are shown to possess remarkable barrier properties, i.e.

![Figure 5 Adsorption Isotherm for pDNA onto PEI-MSNs. Open Access Ref. [118]](image)

**Table 2** Some of the Agricultural Applications of SNPs [61, 75]

| SNPs Size (nm) | Concentration of SNPs | Applications | References |
|---------------|-----------------------|--------------|------------|
| 20–40         | –                     | Enhanced seed viability | [121]       |
| 12            | 8 g L⁻¹               | Improved germination rate and mean germination time | [117]       |
| 15            | 112.5 ppm             | Insecticide | [122]       |
| 10–20         | –                     | Growth inhibition and decreased chlorophyll content in Scenedesmus obliquus | [120]       |
| 15–30         | 200 mg ml⁻¹           | Entomotoxic effect against Sitophilus oryzae | [123]       |
| 50            | 2 g Kg⁻¹              | Insecticide against Tutaabsoluta | [124]       |
| 20–60         | 155 ppm               | Nano-pesticide against Tutaabsoluta | [124]       |
| 80            | 2.06 g Kg⁻¹           | Insecticide against Callosobruchus maculates | [97]        |
| 70–100        | –                     | Controlled delivery system for water-soluble pesticide | [125]       |
|               |                       | Controlled release of avermectin | [126]       |
enhancing of diffusive path for an infiltrate molecule [130, 131]. When it comes to packaging materials, the polyethylene bags pose a great threat to the environment, hence SNPs can be combined with biodegradable polymers to synthesize a safer and reliable substitute for packaging material [132–135].

3.5 Industrial Applications of SNPs

The mesoporous structure and high surface area of SNPs have made them suitable for various industrial applications. Such applications are on the rise due to the extraordinary properties possessed by these particles. For example, mesoporous silica based nano-fibers have shown great potential for immobilization, hence a suitable material for encapsulation [136]. In this respect, Patel et al. [137] used the MSN fibers to successfully encapsulate Horseradish peroxide (HRP) enzyme without losing its activity. Furthermore, using the same fiber matrix, Takeshi et al. [138] encapsulated capsaicin that resulted in the enzyme to have enhanced stimulus activity. This shows the possibility of successful enzymatic encapsulation using MSNs fibers.

Molecularily imprinted polymers (MIPs) are the synthetic polymers obtained by polymerizing functional monomers and crosslinkers in the presence of template [139]. Besides advantages, these synthetic polymers also contain various downsides such as non-uniform distribution of binding sites and irregular size/shapes. To deal with this, the researchers [140] combined SNPs with MIPs to form a hybrid material. The composite was used to detect rhodamine B (RhB) dye. SNPs based MIPs system resulted in improved binding, enhanced RhB detection and superior affinity for RhB. In terms of removing methylene blue, the recent studies by Parida et al. [141] and Leshan et al. [64] are worth mentioning. In the first study, researchers developed functionalized MSNs via one-pot synthesis scheme using phosphate based non-silane precursor. The developed particles consisted 3 types based on NaOH concentration used. The results indicated that the particles involving higher NaOH concentrations showed higher removal efficiencies (Figure 7) [141]. Similarly, in the second study, rice husk was used as a raw material to synthesize amine modified silica nanoparticles using sol-gel route. Cetyltrimethylammonium bromide (CTAB) was used as a structure directing agent. As per results, the highest removal efficiency of 95% was shown by MSN-A particles (Figure 8) [64].

Moreover, SNPs were shown to improve mechanical properties of hybrid polymer when combined with epoxy [142]. Similarly, SNPs combined with alumina showed improved anti wear and antifriction properties [143–147].
Recently, the surface-modified SNPs were developed and successfully applied for oil recovery [148]. Furthermore, Abed and Ali. [149] synthesized environmentally responsive surface-modified SNPs using polyethylene glycol and propyl chains for enhanced oil recovery. Therefore, SNPs are showing promising results as alternatives for chemical surfactants to achieve enhanced oil recovery in oil industries [121].

### 3.6 Environmental Applications of SNPs

Lead contamination in air has become a severe global problem [150]. In this, Yang et al. [151] used electrically charged SNPs exposed to two lead polluted plants to analyze lead adsorption from the atmosphere. The study showed that the SNPs exposed to polluted plants adsorbed more atmospheric lead than without SNPs. Moreover, this was the first study of its kind at the time. One of the recent studies in this direction is by Nashwa et al. [152] where the researchers biosynthesized silica nanoparticles using rice husk. The particles were induced with *Trichoderma harzianum* MF780864 and used for lead removal from water. Figure 9 shows the adsorption capacity of SNPs.

When it comes to applicability of nanoparticles in environmental remediation, the cost and detailed research are the main barriers. He et al. [153] developed MSNPs (Mesoporous Silica Nanoparticles) with larger pore size and higher surface area. The synthesized nanoparticles were used to successfully remove trace mercury from aqueous solutions. Another study [154] infused MSNPs with cellulose acetate, which was used to remove boron up to 93%. Biocides are the chemical substances that are used to control, destroy, render harmless or exert a controlling effect on any harmful organism [155]. Usually, the accumulation of biocides are avoided via soil uptake, however, this procedure poses hazardous dangers for human health as well as environment. This can be resolved by polymer encapsulation. In this, silica based supports have been used by various researchers. One such study [156] used naturally obtained silica as a carrier for neem extract biocide combined with polycarboxylic acid. The study was able to achieve favorable results. Another study [157] used nano-sized paramagnetic zirconia to selectively remove fluoride from a system with metallic as well as non-metallic pollutants. Moreover, SNPs were used to synthesize stable foam for decontaminating radioactive components from the site. It was also shown that increased hydrophobicity stabilized the foam further.

### 3.7 Applications of SNPs in Water Purification

Silica nanoparticles have already been used by various studies to remove heavy metals from aqueous solutions, which validates their use to purify the wastewater generated by industries [158]. Furthermore, the SNPs have been shown to lower or eradicate the biological oxygen demand. Such an BOD activity is more efficient than the conventional non-SNPs based methods [159]. In this, Park et al.
[160] synthesized silver nanoparticles coupled with SNPs to analyze their antimicrobial strength. The study used 2 pathogen viruses; bacteriophage and murine norovirus, in ground, surface, tap and deionized water samples. The coupled silver-silica-nanoparticles (Ag-SNPs) showed higher antiviral strength for murine norovirus than bacteriophage in all 4 types of water samples. Moreover, the antiviral performance of nanoparticles was highly influenced by temperature and organic matter content. The study reveals the possible antiviral use of the silica coupled nanoparticles to kill virus in wastewater. Another study [161] investigated the oil recovery capability of SNPs based film. The researchers used CVD to produce PDMS thin film on SNPs. PDMS being hydrophobic, the film was used to segregate oil from the oil-water mixture. The results were satisfactory and showed the possible use against accidental oil spillage or diffusion that could be detrimental to the environment. Pertaining to oil recovery, another study by Fan et al. [162] synthesized and analyzed the oil recovery factor for polymer-nanosilica, polymer and water flooding. The oil recovery factor for polymer-nanosilica was shown to be highest with 65% compared to polymer 55% and water flooding as 50% respectively (Figure 10).

Similarly, the dye industries are notorious for the release of harmful chemicals into the water streams. These chemicals can ultimately pose great dangers for aquatic as well as human life. Therefore, the need to treat water before being released is an essential step. In this respect, the study [163] used APTES during SNPs synthesis to increase their pore size. The enhanced pore size SNPs were used to analyze the adsorption capacity for Methylene blue dye and the results were satisfactory. Moreover, the pore size was shown to
improve the adsorption capacity significantly. Similarly, another type of dye called Methylene red has detrimental consequences for human health if exposed. For example, it can cause skin/eye irritation and digestive disorders. This dye is mostly used by textile and paper industries [164]. To deal with this, the study [165] synthesized SNPs doped with silver and gold particles, which were used against MR dye as an adsorption medium. The results showed satisfactory catalytic degradation by the manufactured particles against MR dye. Furthermore, in terms of aquatic life, the dyes can block the photosynthetic activity of plants and algae [166]. In this respect, the study [167] developed SNPs coupled with Ag particles as an antifouling adsorbent for effective dye removal and water disinfection. In this respect, few of the most recent works include hybrid SNPs with functionalized mesostructured for methylene blue removal [141] and polysulfone membrane with carbon dots grafted silica for dye removal [168] respectively.

4 Conclusions and Future Prospects

Silica nanoparticles (SNPs) have already found a significantly contributive role in nanotechnology. Enriched with remarkable properties like mesoporous structure, high surface area, tunable particle size, pore size and morphology and biocompatibility offer great advantages in multifaceted applications. These nanoparticles have provided highlighting contributions in the fields like agriculture, food preservation, biomedical and catalytic reactions. SNPs are shown to be excellent encapsulation agents for a wide variety of bioactive molecules, which is already safe proven for targeted drug delivery. Moreover, the feasibility of SNPs to merge with different polymeric as well as non-polymeric materials to form hybrid composites has extended the applicable functionalities even further. Mesoporous Silica nanoparticles (MSNPs) have already shown excellent carrier properties, which is applied in targeting specific cancer cell during chemotherapy. Conclusively, it can be stated that SNPs have proven to be safe, functional and reliable substitute and is finding a growing applicability in almost every field. However, based on the investigative review of this remarkable material and its ever growing applications, the authors believe that the following prospects still need to be further exploited and investigated in future research:

1. Further research is needed to exploit more immobilizing agents compatible with MSNs that can be used for catalytic reaction in a single-pot system without influencing mutual reactivity and system environment. Also need to clarify the optimization conditions for such multi-immobilized MSNs species used in catalytic reaction of single-pot system.
2. There is a room for further research to explore the entrapment capabilities of SNPs for colorless and poorly water-soluble drugs for targeted delivery.
3. Need to unveil more seeds like maize seeds that can develop antifungal properties when coupled with SNPs.
4. Need to investigate that in some crops, the SNPs result in an enhanced stress tolerance in saline conditions while in others, it results in chlorophyl reduction.
5. Chitosan/silica hybrid film is shown to increase shelf life of Loquat fruit. In this respect, need to exploit more fruits that can develop higher shelf life when used with the same hybrid film.
6. More enzymes should be explored and investigated for encapsulation onto MSN fibers.
7. Room for exploring more aminosilanes coupled with SNPs as adsorbents for dye removal from wastewater.

5 Data and Code Availability

The data in this manuscript is available with the corresponding author and can be provided on reasonable request

Author Contributions Faheem Akhter, Ahsan Atta, Mahmood Nabi: Introduction; Synthesis of SNPs; Faheem Akhter, Shafeequ Ahmed, Mukhtiar Ali, Hafiz Anees-ur-Rehman: Applications of SNPs; Faheem Akhter, Zubair Ahmed: Conclusions and Future Prospects

Code Availability Not Applicable

Declarations

Conflict of Interest The authors declare no conflict of interest

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