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Review

Controlled Application of Nanoparticles for Remediation in Oil and Gas Application: Strategies, Challenges, and Innovations

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Abstract: This review provides a detailed examination of strategies for controlling the deposition of nanoparticles in porous media, emphasising the factors influencing their long-term stability and the challenges faced in practical applications. The review explores fundamental mechanisms of nanoparticle retention, including surface modification, intelligent materials, and optimised injection techniques, while discussing environmental and operational variables such as flow velocity, pH, ionic strength, and particle size. The review highlights innovative strategies to maintain nanoparticle stability over time, including responsive ligands, smart nanoparticles, self-healing coatings, and encapsulation techniques. Real-world case studies, including projects from Lockheed Martin, NanoRem, and NANO IRM, illustrate the practical application of these strategies in environmental remediation, emphasising the need for regulatory compliance and long-term monitoring. Overall, this review offers critical insights into the controlled application of nanoparticles for remediation, providing a roadmap for addressing the technical and regulatory challenges associated with their deployment in porous media.

Keywords: nanoparticles; porous media; environmental remediation; controlled deposition; long-term stability

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1. Introduction

1.1. Overview of the Uncontrolled Distribution of Nanoparticles

Nanoparticles are tiny particles with dimensions in the nanometre range, typically between one and one-hundred nanometres. These materials have gained significant attention and application in various fields, including medicine, electronics, and environmental science [1]. Nanoparticles are increasingly used in porous media, such as soils, aquifers, and sediments, for various purposes, from environmental remediation to enhanced oil recovery and targeted drug delivery [2]. The distribution of nanoparticles in porous media, particularly in applications like oil and gas remediation, requires careful control to prevent adverse effects such as environmental contamination and loss of material efficiency [3]. Uncontrolled migration can lead to nanoparticle dispersion in unintended areas, risking groundwater and ecosystem contamination. A controlled application approach can help mitigate these risks by enhancing nanoparticle stability and targeted delivery, ultimately improving both environmental safety and operational efficiency. When nanoparticles are introduced into porous media without a controlled approach, they can migrate uncontrollably and potentially contaminate groundwater, surface water, and ecosystems (Figure 1). This can result in long-term environmental damage and threaten aquatic life and human health.

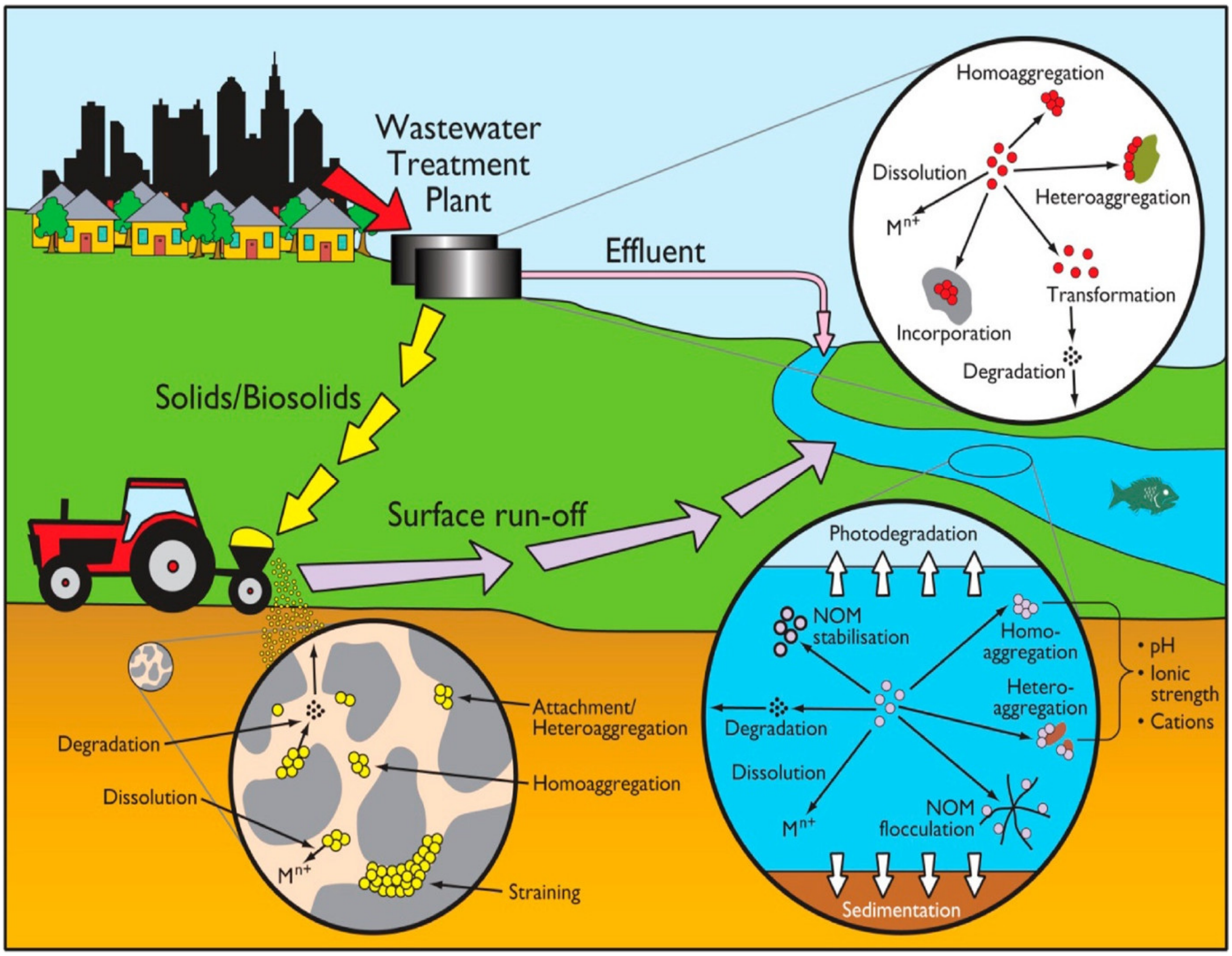

Figure 1. Pathways for releasing nanoparticles into the environment. Diagram includes potential adsorption and desorption effects when nanoparticles interact with soil particles, affecting overall mobility and stability in environmental contexts [4].

Uncontrolled nanoparticle distribution can lead to human exposure through contaminated water sources, inhalation, or direct contact with soil [5]. Some nanoparticles have been associated with adverse health effects, including inflammation, oxidative stress, and potentially carcinogenic properties [6]. A controlled approach is essential to minimising such risks. In applications like environmental remediation, the effectiveness of nanoparticles largely depends on their targeted distribution within porous media [7]. Uncontrolled dispersion can lead to efficient and effective outcomes where the intended benefits may not be realised. Nanoparticles can agglomerate or adhere to the porous media, reducing their long-term stability and effectiveness [8]. A controlled approach involving surface modifications and encapsulation can enhance stability and longevity. Many countries and regulatory bodies have strict guidelines for the use of nanoparticles, especially in environmental and medical applications [9]. The uncontrolled distribution of nanoparticles can result in non-compliance with these regulations, leading to legal and ethical issues. Wastage of nanoparticles due to uncontrolled distribution can be economically detrimental. A controlled approach ensures that resources are used efficiently and reduces the need for additional applications, saving time and money [10]. Overall, a controlled approach to applying nanoparticles in porous media is crucial for addressing the issues mentioned above and realising the full potential of these materials in various fields [11]. Controlling nanoparticle distribution can reduce the risk of environmental contamination and protect ecosystems and water resources. This aligns with responsible and sustainable practices [12].

Furthermore, a controlled approach prioritises human safety by minimising exposure to potentially harmful nanoparticles, thus reducing health risks. Carefully controlling the distribution of nanoparticles ensures that they achieve their intended purposes, leading to more effective outcomes in applications like environmental remediation or enhanced oil recovery [13]. A controlled approach helps organisations and researchers comply with local and international regulations, avoiding legal and ethical complications. Efficient use of nanoparticles through controlled distribution leads to cost savings and a more sustainable approach to nanomaterial applications. The uncontrolled distribution of nanoparticles in porous media can have adverse environmental, health, and economic consequences. Therefore, a controlled approach is necessary for responsible and ethical use and is crucial for maximising the benefits of nanoparticles in various applications.

1.2. Purpose and Scope of Review

This review article extensively examines the multifaceted landscape of controlled deposition of nanoparticles in porous media. This comprehensive review encompasses the entire spectrum of controlled emplacement of nanoparticles, from the influence of their properties and mechanisms of retention to strategies for controlled deposition in porous media and their associated challenges. It also explores the long-term stability of emplaced nanoparticles, shedding light on the opportunities and challenges in this rapidly evolving field.

2. Influence of Nanoparticle Properties on Retention and Emplacement

The properties of nanoparticles play a crucial role in their retention and emplacement in different systems. Several factors influence the fate and behaviour of nanoparticles, including their size, surface chemistry, shape, concentration, and the characteristics of the surrounding environment (Table 1).

Table 1. Influence of nanoparticle properties on their retention in porous media [14].

Nanoparticle Property	Influence on Retention in Porous Media
Size	- Smaller nanoparticles tend to penetrate deeper into porous media. - Larger nanoparticles may be trapped near the entry of porous media. - Size affects the ability to pass through pore throats and void spaces.
Surface Chemistry	- Functionalised surfaces can enhance or reduce interactions with porous media surfaces. - Surface chemistry affects adsorption, wettability, and bonding with the porous matrix.
Shape	- Anisotropic shapes may have different interactions compared to spherical nanoparticles. - Needle-like or plate-like nanoparticles can be preferentially oriented and retained. - Shape can impact the ability to navigate through pore networks.
Coating or Capping Agents	- Coating can stabilise nanoparticles and reduce aggregation, enhancing transport. - Capping agents can influence the wettability of nanoparticles in porous media.
Concentration	- Higher nanoparticle concentrations can lead to increased retention due to crowding effects. - Concentration gradients influence dispersion and deposition in porous media.
Agglomeration State	- Agglomerated nanoparticles may be too large to penetrate porous media effectively. - Aggregation can lead to uneven distribution and trapping in localised regions.
Density	- Higher density particles are more prone to sedimentation, influencing retention depth.
Sedimentation Tendency	- Sedimentation affects the distribution and localization of nanoparticles in media.

One crucial factor influencing nanoparticle retention and emplacement is their size. The size of nanoparticles affects their transport and penetration through different media. Smaller nanoparticles generally have better penetration ability and can easily pass through tiny pores and narrow channels [14]. However, the size of nanoparticles also affects their retention in porous media. Larger nanoparticles may experience more significant retention due to size exclusion and mechanical entrapment [13]. The size of nanoparticles also affects their interaction with cells and tissues. Surface modifications can affect the interaction of nanoparticles with the surrounding environment, including cells, tissues, and porous media. For example, the coating of nanoparticles with osmoprotectants has been shown to prevent temperature-induced aggregation of insulin and retain its native structure [15].

Similarly, the zwitterionic siloxane polymer coating of tantalum oxide nanoparticles reduced their viscosity and tissue retention, making them more suitable as X-ray contrast agents [16]. The shape of nanoparticles also plays a role in their retention and emplacement. Different shapes, such as spherical, rod-like, or branched nanoparticles, have different interaction potentials with cells, tissues, and porous media. For example, spherical nanoparticles have been shown to have better penetration ability and retention in tumour tissues compared to rod-shaped nanoparticles [14]. The shape of nanoparticles can also affect their stability and aggregation behaviour, which can further influence their retention and emplacement. The concentration of nanoparticles is another crucial factor that affects their retention and emplacement. Higher concentrations of nanoparticles can lead to increased aggregation and reduced penetration ability [17]. However, the enhanced permeability and retention effect of tumour tissues can become the dominant factor influencing the efficacy of both passively and actively targeted nanoparticles at higher doses [17]. Therefore, the dosage of nanoparticles needs to be carefully considered when assessing their targeted drug delivery efficacy. The characteristics of the surrounding environment, such as the properties of porous media or biological tissues, also influence nanoparticle retention and emplacement. In porous media, the morphology and surface properties of the media can affect the interaction and retention of nanoparticles [18]. Electrostatic forces and adsorption on pore surfaces can contribute to the retention of nanoparticles in porous media [19]. The retention and emplacement of nanoparticles are influenced by various factors, including their size, surface chemistry, shape, concentration, and the characteristics of the surrounding environment. Understanding these factors is crucial for optimising the design and application of nanoparticles in various fields, including medicine, environmental remediation, and oil recovery. Additional factors, such as particle density and sedimentation tendencies, play crucial roles in nanoparticle retention. Higher-density particles are often more susceptible to sedimentation, significantly impacting their overall distribution and localisation in porous media [10].

3. Mechanisms of Nanoparticle Retention in Porous Media

3.1. Physical Retention Mechanisms

3.1.1. Filtration and Straining

Filtration and straining of nanoparticles in porous media is a complex process influenced by various factors. The mechanism of filtration and straining involves the interaction between nanoparticles and the porous media, the physicochemical properties of the nanoparticles, and the flow conditions in the porous media [20]. One crucial factor that affects the filtration and straining of nanoparticles is the size of the nanoparticles (Table 2). Smaller nanoparticles are more likely to pass through the pores of the porous media, while larger nanoparticles arising from aggregation may get trapped and retained in the media [8]. Adsorption in porous media can be broadly classified as physical or chemical. Physical adsorption typically involves van der Waals forces, while chemical adsorption entails stronger bonds, often covalent, with the porous media surface [19]. This distinction is relevant in applications where the durability and reversibility of nanoparticle adhesion are critical factors.

Table 2. Nanoparticles' physical and chemical retention mechanisms in porous media and impact of aggregation [21].

Mechanism	Description	Impact of Aggregation
Physical Retention	1. Straining: Larger nanoparticles may get trapped in smaller pore throats. 2. Filtration: Smaller nanoparticles can be retained by physical filtration. 3. Sedimentation: Gravitational settling of nanoparticles 4. Advection: Nanoparticles carried by fluid flow	Aggregation can increase the effective size of nanoparticles, enhancing straining and filtration effects. It may lead to more significant physical retention.
Chemical Retention	1. Adsorption: Nanoparticles can adhere to the porous media's surfaces. 2. Surface Modification: Engineered surface coatings on nanoparticles.	Aggregation may change the surface properties of nanoparticles, affecting their adsorption behaviour. Aggregates might exhibit different adsorption characteristics compared to individual particles.

The size of the nanoparticles also affects their mobility in the porous media. Smaller nanoparticles are highly mobile due to their small size relative to the pore spaces, which allows them to effectively transport through the media [22]. On the other hand, larger nanoparticles may experience hindered transport and deposition due to their size [23]. The physicochemical properties of the nanoparticles, such as surface charge and surface chemistry, also play a significant role in their filtration and straining behaviour in porous media. The surface charge of the nanoparticles can influence their interaction with the charged surfaces of the porous media. For example, nanoparticles with the same surface charge as the porous media are more stable and less likely to be filtered out [24]. The surface chemistry of the nanoparticles can also affect their adsorption onto the pore surfaces, which can lead to aggregation and deposition in the porous media [19]. The flow conditions in the porous media, such as flow rate and solution chemistry, also impact the filtration and straining of nanoparticles. The flow rate affects the residence time of the nanoparticles in the porous media, which can influence their deposition and retention [8]. The solution chemistry, including ionic strength, pH, and natural organic matter, can affect the interactions between the nanoparticles and the porous media surfaces [8]. Depending on the specific conditions, these interactions can be dominated by physicochemical or electrostatic forces [25].

Furthermore, the structure and properties of the porous media itself, such as pore size and organisation, also influence the filtration and straining of nanoparticles. The pore size and organisation determine the size exclusion effect, where particles larger than the pore size are more likely to be filtered out [8]. The surface roughness of the porous media can also affect the interactions between the nanoparticles and the media surfaces [8]. Additionally, other substances in the porous media, such as natural organic matter or other particles, can interact with the nanoparticles and affect their filtration and straining behaviour [26]. In general, the mechanism of filtration and straining of nanoparticles in porous media is a complex process influenced by various factors, including the size and physicochemical properties of the nanoparticles, the porous media's flow conditions, and the media's structure and properties. Understanding these mechanisms is crucial for environmental monitoring, water purification, and enhanced oil recovery applications.

3.1.2. Diffusion and Brownian Motion

Diffusion and Brownian motion are key mechanisms influencing nanoparticle transport within porous media [27]. Brownian motion, driven by random thermal movements, allows nanoparticles, especially those with smaller sizes, to interact with pore walls. Such motion can counteract sedimentation and contribute to uniform distribution, aiding applications like enhanced oil recovery [28]. Key influencing factors—including nanoparticle size, surface properties, and porous media structure—play a role in these mechanisms. However, they are not mechanisms themselves but modifiers of diffusion and retention behaviours [26]. Diffusion of nanoparticles in porous media is a complex process that involves several mechanisms. Nanoparticle size, surface properties, pore size distribution, and flow conditions influence the transport of nanoparticles in porous media. Understanding the diffusion mechanism of nanoparticles in porous media is crucial for various applications, including enhanced oil recovery, water purification, and environmental remediation (Franco et al., 2013) [13]. One of the critical factors influencing nanoparticle diffusion in porous media is their size. Nanoparticles are much smaller than the relevant pore spaces in porous media, which allows them to transport through the pores effectively [22]. The small size of nanoparticles enables them to penetrate the narrowest pore throats and access regions inaccessible to larger particles [22]. This high mobility of nanoparticles in porous media is advantageous for various applications, as it allows for efficient transport and distribution of nanoparticles throughout the porous matrix [26]. The surface properties of nanoparticles also play a significant role in their diffusion in porous media. The adsorption of nanoparticles onto the surfaces of porous media can affect their transport behaviour. For example, the adsorption of asphaltenes onto nanoparticles can inhibit their precipitation and deposition on rock surfaces, thereby enhancing the perdurability against asphaltene damage in porous media [22]. The adsorption equilibrium of asphaltenes onto nanoparticles can be achieved relatively quickly, indicating the promising nature of adsorbents for delaying the agglomeration and inhibiting the precipitation and deposition of asphaltenes [22]. The flow conditions in porous media, such as the velocity and pressure, also influence the diffusion of nanoparticles. The fluid flow velocity can affect nanoparticles' transport behaviour in porous media. Lower flow velocities can lead to the deposition of nanoparticles and the formation of aggregates in porous media. In comparison, higher flow velocities can enhance the transport of nanoparticles through the porous matrix [29]. The pressure conditions, such as reservoir pressure and temperature, can also affect the transport of nanoparticles in porous media [22].

Furthermore, the structure and properties of the porous media itself can influence the diffusion of nanoparticles. The distribution of pore sizes and the tortuosity of the porous media can affect the transport behaviour of nanoparticles. The tortuosity factor, which describes the deviation of the diffusion path from a straight line due to the complex pore structure, can impact the diffusion of nanoparticles in porous media [30]. The anisotropy of porous media properties, such as permeability and porosity, can also influence the transport of nanoparticles [31]. Several mechanisms, including nanoparticle size, surface characteristics, flow conditions, and the structure of the porous media, play a role in the diffusion of nanoparticles within porous media. The small size of nanoparticles facilitates their high mobility in porous media, while their surface characteristics and adsorption behaviour can affect their transport behaviour. Flow conditions and the structure of the porous media also significantly influence the diffusion of nanoparticles. Understanding these mechanisms is vital for designing and optimising applications for nanoparticle transport in porous media.

3.1.3. Sedimentation and Gravitational Settling

The mechanism of sedimentation and gravitational settling of nanoparticles in porous media is a complex process that involves various factors and interactions. Several studies have investigated this phenomenon and provided insights into the underlying mechanisms. One crucial factor that affects the sedimentation and gravitational settling of nanoparticles in porous media is the size of the nanoparticles (Table 2). Nanoparticles are much smaller than the relevant pore spaces in porous media, which allows for effective transport [22]. The small size of nanoparticles enables them to move through the pore spaces and settle under the influence of gravity [32]. The gravitational effect on nanoparticles is generally considered negligible compared to other mechanisms, such as interception and diffusion [33]. However, the size of nanoparticles can favour their aggregation and gravitational settling in porous media, as indicated in Table 2 [8]. Aggregation of nanoparticles enhances their deposition, but aggregates that are not removed will sample a smaller portion of the available pore network within the column due to size exclusion [8]. The flow velocity of the fluid through the porous media is another significant factor affecting nanoparticle sedimentation and gravitational settling. The velocity determines the density and location of aggregate deposition in porous media [29]. Higher flow velocities can lead to the formation of aggregates and their subsequent deposition in the porous media [29]. The flow direction, whether vertically downward, horizontally, or vertically upward, can also affect nanoparticles' gravitational settling in porous media [32]. The heterogeneity of the porous media, including pore size and organisation, also influences the deposition and mobility of nanoparticles. The transport of nanoparticles in porous media is affected by the conditions at which they interact with the media [12].

3.2. Chemical Retention Mechanisms

3.2.1. Adsorption and Surface Interactions

The adsorption mechanism of nanoparticles in porous media is a complex process influenced by various factors. Several studies have investigated the adsorption and transport of nanoparticles in porous media, particularly in the context of environmental monitoring, enhanced oil recovery, and water purification. One crucial factor that affects the adsorption of nanoparticles in porous media is the physicochemical properties of the nanoparticles and the porous media surfaces [34]. The interactions between nanoparticles and the surfaces of porous media can be influenced by factors such as surface charge, surface roughness, and surface chemistry [35]. For example, the surface charge of nanoparticles and the surface charge of the porous media can determine the electrostatic interactions between the nanoparticles and the porous media surfaces [19]. Additionally, the porous media's surface roughness can affect nanoparticles' adsorption by providing more surface area for interaction [36]. Surface chemistry significantly influences nanoparticle adsorption. For instance, Zhu et al. (2015) [37] demonstrated that chemically modified surfaces on nanoparticles enhanced their interaction with porous media, suggesting improved retention potential in oil reservoir applications. The size of the nanoparticles is another critical factor influencing their adsorption in porous media (Table 3).

Table 3. Impact of nanoparticle size on retention in porous media [38].

Nanoparticle Size	Influence on Retention in Porous Media
Larger particles (e.g., >100 nm)	1. Greater tendency for physical trapping in pore throats. 2. Reduced mobility and penetration into smaller pores. 3. Enhanced gravitational settling, leading to faster deposition.
Intermediate Nanoparticles (e.g., 10–100 nm)	1. Moderate mobility and retention behaviour. 2. Partial penetration into smaller pores. 3. Retention is influenced by surface properties and electrostatic interactions.
Smaller Nanoparticles (e.g., <10 nm)	1. Higher mobility and penetration capability due to size. 2. Lower physical trapping in pore throats. 3. Greater susceptibility to interactions with porous media surfaces. 4. Potential for surface charge effects on retention.

Nanoparticles are typically much smaller than the pore spaces in porous media, which allows them to flow more quickly through the porous media [39]. However, even though nanoparticles can pass through the pore throats, they can still be retained in the porous media due to physicochemical attractions between the nanoparticles and the pore walls [39]. The adsorption of nanoparticles onto the pore surfaces can occur through various mechanisms, including gravitational sedimentation, interception, straining, and mechanical trapping [40]. Other substances, such as organic matter, surfactants, and polymers, can also influence the adsorption of nanoparticles in porous media. These substances can compete with nanoparticles for adsorption sites on porous media surfaces, leading to changes in the adsorption behaviour [41]. Additionally, the physicochemical parameters of the solution, such as pH, ionic strength, and the presence of natural organic matter, can affect the interactions between nanoparticles and the porous media surfaces [8]. The adsorption of nanoparticles in porous media can have significant implications in various applications. For example, in the context of enhanced oil recovery, the adsorption of nanoparticles onto the rock surfaces can alter the wettability of the rock and improve the efficiency of injection fluids for sweeping [42]. In water purification, the adsorption of nanoparticles onto the pore surfaces can enhance the removal of contaminants from aqueous solutions [26]. The adsorption mechanism of nanoparticles in porous media is a complex process that is influenced by factors such as the physicochemical properties of the nanoparticles and the porous media surfaces, the size of the nanoparticles, the presence of other substances, and the physicochemical parameters of the solution. Understanding these factors is crucial for optimising the adsorption and transport of nanoparticles in porous media for various applications.

3.2.2. Multilayer Adsorption

Multilayer adsorption of nanoparticles in porous media refers to nanoparticles forming multiple layers on the surfaces of porous materials (Figure 2). This phenomenon has been studied in various contexts, including the aggregation and deposition of nanoparticles in porous media [8], the mobility of nanoparticles in porous media [22], and the adsorption of nanoparticles during transport in porous media [43]. The multilayer adsorption of nanoparticles in porous media is influenced by several factors, including the physicochemical properties of the nanoparticles, the properties of the porous media, and the operating conditions.

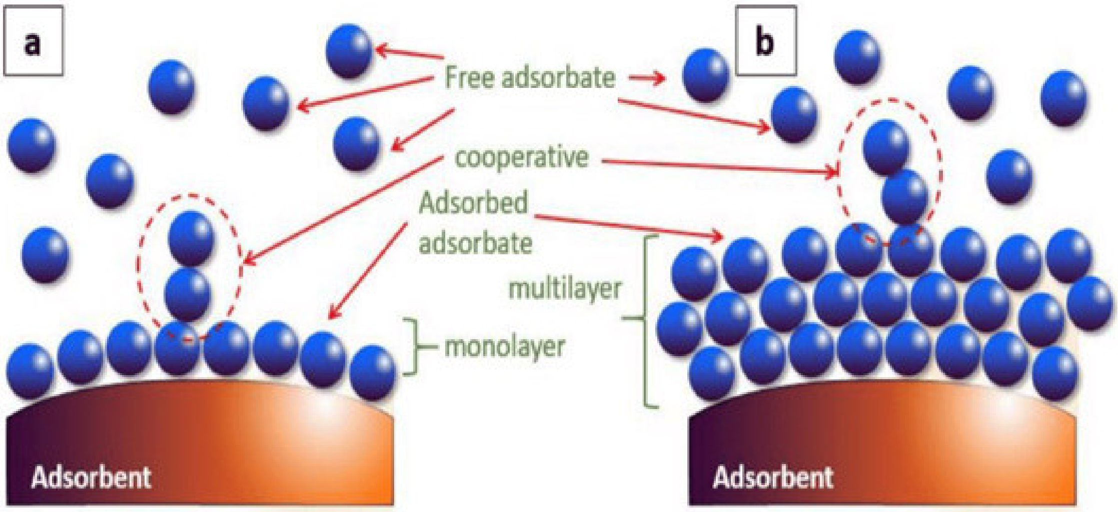

Figure 2. Multilayer adsorption mechanism of nanoparticles in porous media [44]. (**a**) monolayer; (**b**) multi-layer.

For example, nanoparticles' size and surface properties can affect their adsorption behaviour in porous media [45]. Other substances, such as natural organic matter or surfactants, can also influence the adsorption of nanoparticles in porous media [46]. The formation of multilayer adsorption of nanoparticles in porous media can be achieved through various mechanisms, such as layer-by-layer assembly techniques [47]. These techniques involve the sequential adsorption of oppositely charged nanoparticles onto porous substrates. The multilayer growth can be controlled or influenced by the assembly conditions, such as the pH of the solution or the charge density of the nanoparticles [48]. The multilayer adsorption of nanoparticles in porous media has important implications in various fields. In environmental science, it can affect the transport and fate of nanoparticles in natural systems, such as groundwater or soil [49]. Materials science can fabricate functional materials with tailored properties [50]. In the context of oil and gas production, the multilayer adsorption of nanoparticles in porous media can impact the efficiency of enhanced oil recovery processes and the prevention of asphaltene deposition [51]. Also, nanoparticles are used for site remediation in oil and gas applications. For example, silica-based nanoparticles are injected into contaminated groundwater to promote the adsorption of hydrocarbons onto nanoparticle surfaces, mitigating spread and easing subsequent cleanup [52]. Moreover, responsive nanoparticles that adjust their surface charge under varying pH conditions can localise within oil spill-affected zones, creating targeted remediation zones (Zhang et al., 2019) [53]. Overall, the multilayer adsorption of nanoparticles in porous media is a complex phenomenon influenced by various factors. Understanding and controlling this process is crucial for multiple applications, from environmental remediation to materials synthesis and oil recovery.

3.3. Electrostatic and Steric Mechanisms

Nanoparticles in porous media can experience electrostatic and steric effects that influence their behaviour and transport properties [37]. Electrostatic effects arise from the interaction between charged nanoparticles and the charged surfaces of the porous media. In contrast, steric effects result from the physical hindrance caused by the size and shape of the nanoparticles. Electrostatic effects play a significant role in the transport of nanoparticles through porous media [33]. The surface charge of both the nanoparticles and the porous media can lead to attractive or repulsive forces, thereby affecting their mobility. For instance, nanoparticles with a positive surface charge may experience electrostatic repulsion from positively charged surfaces in the porous media as shown in Table 4, which enhances mobility [33].

Table 4. Combined effect of surface charge and size of nanoparticles on retention in porous media [22].

Surface Charge	Size	Influence on Retention in Porous Media
Neutral	Small	Limited retention due to weak electrostatic interactions with porous media surfaces.
Neutral	Large	Enhanced retention compared to small neutral nanoparticles due to size-related effects (sieving).
Positively Charged	Small	Strong electrostatic interactions with negatively charged porous media, leading to enhanced retention.
Positively Charged	Large	High retention due to a combination of electrostatic interactions and size-related effects.
Negatively Charged	Small	Electrostatic repulsion from negatively charged porous media, resulting in reduced retention.
Negatively Charged	Large	Moderate to high retention due to size-related effects outweighing electrostatic repulsion.
Variable Charge (pH-dependent)	Small	Retention is highly dependent on pH conditions, with both electrostatic and size effects in play.
Variable Charge (pH-dependent)	Large	pH-dependent retention with stronger size-related effects at higher pH values.

On the other hand, nanoparticles with a negative surface charge may experience electrostatic repulsion from negatively charged surfaces, resulting in reduced mobility [25]. The system's pH can also influence the surface charge and, consequently, the electrostatic interactions between nanoparticles and porous media [33]. Steric effects, on the other hand, arise from the physical hindrance caused by the size and shape of the nanoparticles. Nanoparticles are much smaller than the pore spaces in porous media, allowing them to move more freely than larger particles [22]. This size difference reduces the likelihood of particle–particle and particle–pore interactions, leading to enhanced mobility [22]. Additionally, the shape of nanoparticles can also affect their transport properties. For example, nanoparticles with elongated shapes may experience less hindrance and more mobility than spherical nanoparticles [54]. The combined effect of electrostatic and steric interactions determines the overall behaviour of nanoparticles in porous media. The surface coatings of nanoparticles can induce electrostatic and/or steric repulsions, promoting their transport in porous media [55]. The presence of other substances, such as dissolved organic matter, can also influence the transport of nanoparticles by altering their surface charge and interactions with the porous media [56]. Understanding nanoparticles' electrostatic and steric effects in porous media is crucial for various applications, including enhanced oil recovery and environmental remediation. By manipulating nanoparticles' surface charge and shape, researchers can optimise their transport properties and improve their efficiency in these applications [57]. Furthermore, studying the transport of nanoparticles in porous media can provide insights into the fundamental mechanisms of mass transport and diffusion in complex porous structures [58]. Overall, electrostatic and steric effects play significant roles in the transport of nanoparticles in porous media. The surface charge and pH of the system influence the electrostatic interactions between nanoparticles and porous media, while the size and shape of nanoparticles determine the steric hindrance they experience. Understanding and controlling these effects is essential for optimising the transport and behaviour of nanoparticles in various applications.

4. Strategies for Controlling Nanoparticle Deposition in Porous Media

The transport and retention of nanoparticles in porous media are influenced by various factors, including the size and surface chemistry of the nanoparticles, the properties of the porous media, and the flow conditions [59]. Overall, strategies for controlled injection and emplacement of nanoparticles in porous media involve modifying the surface chemistry of the nanoparticles, considering the size and properties of the nanoparticles, understanding the characteristics of the porous media, and accounting for the flow conditions [60]. These strategies can face several challenges, as shown in Table 5 below.

Table 5. Strategies for controlled injection and deposition of nanoparticles in porous media and its associated challenges [12].

Strategy	Description	Challenges
Surface Modification	Modifying nanoparticle surface properties to enhance stability and control.	- Achieving uniform surface modification - Maintaining surface modifications during transport - Compatibility with porous media surfaces
Smart Materials	Using nanoparticles with responsive properties to control deposition.	- Designing responsive nanoparticles - Achieving precise triggering mechanisms - Compatibility with target porous media
Injection Strategies	Controlling the injection process to optimise nanoparticle transport and deposition.	- Achieving uniform injection rates - Navigating complex porous media geometries - Minimising injection-induced heterogeneity
Stabilisation Techniques	Methods to prevent nanoparticle aggregation and improve stability during transport.	- Selection of suitable stabilisers - Effective dispersion mechanisms - Compatibility with target media conditions - Use of stabilizing agents and density modifiers to prevent rapid settling
In Situ Monitoring	Real-time monitoring of nanoparticle behaviour for feedback and control.	- Developing suitable monitoring techniques - Achieving sufficient resolution for small-scale events - Implementing monitoring in practical applications
Responsive Nanoparticles	Nanoparticles that respond to specific conditions in porous media.	- Designing nanoparticles with desired responsiveness - Ensuring rapid and reliable responses - Avoiding unintended reactions or responses
Flow Control	Adjusting fluid properties or flow parameters to influence nanoparticle deposition.	- Identifying optimal flow control parameters - Minimising impact on overall fluid flow - Achieving fine-tuned control in complex media
Functionalisation Techniques	Attaching functional groups or molecules to nanoparticles to control interactions.	- Selection of appropriate functional groups - Ensuring stability and reactivity of functionalised nanoparticles - Compatibility with target media surfaces
Injection Control Systems	Implementing automated systems for precise control of nanoparticle injection.	- Developing reliable and robust control systems - Integrating with existing infrastructure and equipment - Ensuring safety and fail-safes in control systems
Real-Time Feedback Systems	Using feedback loops to adjust injection parameters based on monitoring data.	- Developing algorithms for real-time decision-making - Minimising delays in feedback responses - Incorporating multiple sensor inputs for accuracy

One strategy for controlled injection and emplacement of nanoparticles is to modify the surface chemistry of the nanoparticles to enhance their transport in porous media. For example, surfactants and natural organic matter (NOM) can disperse nanoparticles and promote their transport in saturated porous media [61]. Additionally, polymer coatings on nanoparticles can affect their deposition and retention in porous media [62]. The surface chemistry of the porous media itself also plays a role in nanoparticle transport, as interactions between the nanoparticles and the pore walls can lead to adsorption or retention [63]. The size of the nanoparticles is another essential factor to consider. Nanoparticles with larger aggregate sizes may experience increased deposition in porous media due to pore straining and gravitation sedimentation [61]. Stabilising agents and density modifiers can be employed to address sedimentation challenges, reducing nanoparticle settling rates and ensuring more even distribution within the porous medium [64].

On the other hand, near-neutrally buoyant colloids with radii in the range of 100 nm to 1 µm can exhibit reduced retention in non-target porous media, allowing for targeted delivery [65]. The properties of the porous media, such as porosity and heterogeneity, can significantly impact the transport and deposition of nanoparticles. Heterogeneity in hydraulic conductivity, for example, can affect the deposition of nanoparticles in porous media [66]. The particles and suspension media's nature can also influence nanoparticles' retention and mobility in porous media [67]. Flow conditions, including velocity and pressure, can also affect nanoparticle transport in porous media. The velocity of the flow can influence the deposition of nanoparticles, with higher velocities favouring deposition due to hydrodynamic, gravitational, and inertial effects [67]. Pressure conditions, such as those encountered in the SAGD process, can impact the propagation of nanoparticles in oil sand media [68]. These strategies and associated challenges are critical in achieving controlled injection and deposition of nanoparticles in porous media for various applications, including enhanced oil recovery and groundwater remediation. It is crucial to address these challenges to optimise nanoparticle-controlled delivery and maximise the benefits of porous media applications.

5. Long-Term Stability of Emplaced Nanoparticles

5.1. Factors Affecting the Stability of Deposited Nanoparticles

Various factors influence the long-term stability of deposited and emplaced nanoparticles in porous media. These factors include flow velocity, solution pH, ionic strength, cation or salt type, presence of a coating, particle concentration, particle size, surface charges, nature of the stationary porous media, nature of flow rate, temperature, pressure, flow channels, shear variation, suspension media, presence of humic acid, and pore morphology, with surface chemistry being the key determinant [21]. Flow velocity plays a significant role in nanoparticle transport and deposition in porous media. Lecoanet and Wiesner (2004) [21] found that flow velocity affects the deposition of fullerene and oxide nanoparticles in porous media. They observed that higher flow velocities resulted in increased deposition of nanoparticles. Solution pH and ionic strength also influence the stability and transport of nanoparticles in porous media. Ref. [36] reported that the dispersion stability of TiO_2 nanoparticles in aqueous suspensions is mainly governed by solution pH and ionic strength. They found that the mobility of TiO_2 nanoparticles in porous media is affected by these factors. The valence of cation or salt type can affect the stability and transport of engineered nanoparticles (ENPs) in porous media. Ref. [47] highlighted the role of cation or salt type in affecting the stability and transport of ENPs in porous media. A coating on nanoparticles can enhance their long-term colloidal stability in biological media. Ref. [5] observed that functionalised nanoparticles with a highly dense and stable polyethylene glycol (PEG) coating exhibited prolonged colloidal stability in biological media. Particle concentration is another factor affecting nanoparticle retention and transport in porous media. Ref. [46] investigated the effect of particle concentration on the retention and transport of silica nanoparticles in saturated porous media. They found that particle concentration influenced the retention and transport of nanoparticles. Particle size and surface charges also play a role in the stability and transport of nanoparticles in porous media [36]. Ref. [27] studied the transport of polymer-coated metal-organic framework nanoparticles in porous media and found that factors such as size and surface charges influenced their transport. The nature of the stationary porous media and the nature of the flow rate can affect the transport and deposition of nanoparticles. Ref. [10] highlighted the influence of these factors on the transport and deposition of silver nanoparticles in porous media. Temperature, pressure, flow rate conditions, and the nature of the particles and the suspension media can significantly impact the retention and mobility of nanoparticles in porous media. Ref. [31] emphasised the role of these factors in the deposition of dispersed nanoparticles in porous media. The presence of humic acid in aquifers and porous media, the pH range of natural water, and the slow water speed can enhance iron oxide nanoparticles' stability and mobility in natural water and porous media. Ref. [1] discussed the influence of these factors on the stability and transportation of iron oxide nanoparticles. The variation of shear associated with complex pore morphology and the interactions between nanoparticles and tortuous flow channels can affect the viscosity of nanoparticle dispersion in porous media. Ref. [25] investigated the viscosity of silica nanoparticle dispersions in permeable media and highlighted the influence of these factors. In addition to the factors mentioned above, other factors such as surfactants, electrostatic forces, aggregation, and adsorption on pore surfaces can also affect the fate, transport, and deposition of nanoparticles in porous media [28].

5.2. Ageing and Degradation of Deposited Nanoparticles with Time

Nanoparticle degradation in porous media can occur due to various mechanisms, which are influenced by factors such as the nanoparticle composition, environmental conditions, and the characteristics of the porous media [27,28]. Some common mechanisms of nanoparticle degradation in porous media include:

(a) Chemical Reactions:
   - Oxidation: Nanoparticles may react chemically with oxygen or oxidising agents in the porous media [26]. This can lead to the formation of oxides or other degradation products.
   - Dissolution: Nanoparticles made of materials like metals or metal oxides can dissolve in acidic or alkaline conditions, leading to their degradation [25].

(b) Surface Coating Erosion: The protective coatings on nanoparticles may erode over time, exposing the core material to the surrounding environment. This can occur due to abrasion, chemical interactions, or changes in pH [10].

(c) Agglomeration: Nanoparticles may agglomerate or aggregate in porous media, reducing their surface area and reactivity. This can limit their effectiveness and may be considered a form of degradation, particularly in applications where dispersal is crucial [21,22].

(d) Biological Interactions: Microorganisms present in porous media can interact with nanoparticles. Some microorganisms can biodegrade nanoparticles through enzymatic reactions, leading to their transformation or degradation. Microbial biofilm formation on nanoparticle surfaces can also change the nanoparticle's behaviour and lead to degradation over time [13].

(e) Physical Weathering: Nanoparticles may undergo physical changes due to mechanical forces, such as erosion, shearing, or grinding, caused by the movement of porous media. These physical stresses can result in particle degradation [18].

(f) Electrochemical Reactions: In environments with varying electric potential, nanoparticles may undergo electrochemical reactions that cause degradation. For example, electrochemical corrosion of metallic nanoparticles can occur in certain conditions.

(g) Changes in Environmental Conditions: Variations in temperature, pH, and ionic strength in the porous media can impact nanoparticle stability. Extreme conditions may accelerate degradation, while more stable conditions prolong nanoparticle lifespan.

(h) Ageing Effects: Over time, nanoparticles can naturally age, leading to changes in their physical and chemical properties. This ageing can result from a combination of the earlier mechanisms and may be accelerated or slowed down based on environmental conditions.

Understanding these mechanisms of nanoparticle degradation in porous media is crucial for designing and implementing practical nanoparticle-based applications and assessing their long-term environmental impact. Based on this understanding, strategies may be developed for enhancing nanoparticle stability and controlling their distribution within porous media.

5.3. Strategies for Maintaining Stability of Deposited Nanoparticles

Maintaining the stability of deposited nanoparticles over extended periods is essential for various applications, such as environmental remediation [33]. Innovative approaches have been developed to address the challenges of enhancing the long-term stability of deposited nanoparticles in porous media. Some of the developed innovative strategies for extending the long-term stability of deposited nanoparticles include the following:

(a) Surface Modification with Responsive Ligands: Functional ligands attached to the nanoparticle surface can respond to environmental changes, helping to prevent instability. For example, pH-responsive ligands can regulate the interaction between nanoparticles and their surroundings [39].

(b) Smart Nanoparticles: These nanoparticles are designed with responsive properties that adapt to changing conditions. For instance, they can expand or contract in response to pH or ionic strength variations, which helps maintain their stability and prevent agglomeration.

(c) Self-Healing Coatings: Researchers have developed self-healing coatings for nanoparticles. When the coating is damaged, it can repair itself, preserving the integrity of the nanoparticles. This is particularly useful in harsh or dynamic environments [40].

(d) Nanoparticle Encapsulation: Encapsulation involves embedding nanoparticles within protective shells or matrices. These shells can be made from biocompatible polymers or materials that are stable in the intended application environment, ensuring long-term stability [19].

(e) Responsive Gels: Responsive hydrogels can be used to entrap nanoparticles. These gels can swell or contract in response to environmental changes, helping to regulate the release and stability of the deposited nanoparticles [21].

(f) Nanostructured Porous Media: Designing the porous media to have a nanostructured surface can help immobilise nanoparticles effectively and extend the stability of deposited nanoparticles [32]. This approach can be particularly valuable in environmental remediation.

These innovative approaches demonstrate the dynamic nature of nanoparticle stability research, providing solutions that can be tailored to specific applications and environments. The choice of approach depends on factors like the application, the nature of the nanoparticles, and the intended duration of stability. However, some of the challenges associated with these innovative strategies are summarised in Table 6.

Table 6. Limitations of some existing strategies for maintaining stability of deposited nanoparticles in porous media.

Approach	Challenges
Surface Modifications	1. Limited long-term stability due to potential desorption and reactivity of surface-modified groups. 2. Complex synthesis and characterisation processes.
Encapsulation/Coating	1. Selection of suitable encapsulating materials and methods. 2. Ensuring uniform and complete coverage of nanoparticles. 3. Potential release of encapsulated materials over time.
Hybrid Nanostructures	1. Integration of different materials with varying stabilities. 2. Maintaining the stability of the interfaces between nanoparticle components. 3. Complexity in material selection and synthesis.
Smart Responsive Materials	1. Design and fabrication of responsive materials that can adapt to changing conditions. 2. Ensuring long-term responsiveness without deterioration. 3. Limited applications for certain responsive materials.
Green/Sustainable Approaches	1. Finding eco-friendly methods and materials that are also stable over time. 2. Balancing stability and sustainability. 3. Limited availability of green alternatives for specific applications.

5.4. Long-Term Environmental Impact of Nanoparticles

The long-term environmental impact of nanoparticles (NPs) is an increasingly critical area of research, particularly concerning their toxicity and interactions within ecosystems. Nanoparticles, due to their unique physicochemical properties, exhibit behaviours that can significantly differ from their bulk counterparts, leading to potential ecological risks. This discussion synthesises findings from various studies, highlighting the toxicity of nanoparticles, their interactions with biological systems, and case studies that provide environmental monitoring data. Several factors, including size, shape, surface charge, and chemical composition influence nanoparticle toxicity. For instance, studies have shown that smaller nanoparticles often exhibit higher toxicity due to their increased surface area, which enhances their reactivity and interaction with biological systems [54]. The mechanisms of toxicity can vary widely; for example, titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles have been reported to induce oxidative stress in cells, leading to cellular damage and apoptosis [55,56]. Furthermore, the presence of specific elements, such as cobalt in alloy nanoparticles, can exacerbate toxicity by promoting the formation of reactive oxygen species (ROS) [57]. The ecological implications of nanoparticle toxicity are profound, particularly in aquatic environments. Research has demonstrated that nanoparticles can accumulate in organisms, leading to bioaccumulation and biomagnification within food webs. For example, a study on Daphnia magna revealed that titanium dioxide nanoparticles could accumulate and distribute within the organism, posing risks to aquatic ecosystems [58]. Similarly, the comparative toxicity of metallic nanoparticles, such as copper and chromium, has been shown to vary significantly depending on environmental conditions and the presence of other substances, leading to complex interactions that can alter toxicity profiles [59]. Case studies provide valuable insights into the real-world implications of nanoparticle exposure. For instance, the introduction of nano-fertilizers in agriculture has raised concerns regarding their long-term environmental impact, particularly regarding the accumulation of nanoparticles in soil and water systems [59,60]. Monitoring data from various studies indicate that nanoparticles can persist in the environment, potentially affecting soil health and aquatic life. Moreover, the interaction of nanoparticles with pollutants can either mitigate or exacerbate toxicity, as observed in studies where nanoparticles were shown to alter the bioavailability of airborne pollutants [54,61]. In addition to direct toxicity, nanoparticles can influence ecosystem dynamics. For example, the presence of nanoparticles in the environment can affect microbial communities, which play crucial roles in nutrient cycling and ecosystem functioning. The toxicity of nanoparticles to bacteria and other microorganisms can disrupt these processes, leading to broader ecological consequences [62,63]. Furthermore, the physicochemical properties of nanoparticles can change under environmental conditions, such as exposure to sunlight, which can enhance their toxic potential [64]. The long-term environmental impact of nanoparticles is multifaceted, encompassing direct toxicity to organisms, potential bioaccumulation, and alterations to ecosystem dynamics. Ongoing research is essential to fully understand these impacts, particularly as the use of nanoparticles in various industries continues to grow. Comprehensive environmental monitoring and risk assessment frameworks are necessary to evaluate the safety and sustainability of nanoparticle applications.

5.5. Predictive Modelling Approaches for Nanoparticle Transport in Porous Media

Numerical simulation and mathematical modelling have been employed to gain insights into the behaviour of nanoparticles in porous media. Continuum-based models (Table 7) have been developed to describe the transport of nanoparticles in porous media and account for various transport mechanisms, such as irreversible deposition, attachment/detachment, agglomeration, physical straining, site-blocking, ripening, and size exclusion [66].

Table 7. Continuum models used for describing nanoparticle transport in porous media [66].

Transport Model	Mechanisms	Fitting Parameters
$\frac{\rho_b}{\theta_W}\left(\frac{dS}{dt}\right) = k_{att}C$	Attachment	k_{att}
$\frac{\rho_b}{\theta_W}\left(\frac{dS}{dt}\right) = k_{att}C - \frac{\rho_b}{\theta_W}k_{det}S$	Attachment/Detachment	k_{att}, k_{det}
$\frac{\rho_b}{\theta_W}\left(\frac{dS}{dt}\right) = k_{att}C - \frac{\rho_b}{\theta_W}f_r k_{det}S$	Attachment and dual site detachment	k_{att}, k_{det}, f_r
$\frac{dS}{dt} = \frac{dS_1}{dt} + \frac{dS_2}{dt}$ $\frac{\rho_b}{\theta_W}\left(\frac{dS_1}{dt}\right) = k_{att1}C - k_{det1}\rho_b S_1$ $\frac{\rho_b}{\theta_W}\left(\frac{dS_2}{dt}\right) = k_{att2}C - k_{det2}\rho_b S_2$	Dual site attachment/detachment	k_{att1}, k_{att2}, k_{det1}, k_{det2}
$\frac{dC}{dt}\left(1 + \frac{\rho_b}{\theta_W}K_d\right) = D\frac{\partial^2 C}{\partial x^2} - v\frac{dC}{dx} + k_{att}C$	Attachment, adsorption (retardation)	k_{att}, K_d
$\frac{\rho_b}{\theta_W}\left(\frac{dS}{dt}\right) = k_{rel}\frac{\rho_b}{\theta_W}(S - S_{eq})H_o(S - S_{eq})$ $S_{eq} = f_{nr}S_i$	Release after perturbation	k_{rel}, f_{nr}

These models have successfully described the simultaneous occurrence of multiple transport mechanisms and can be scaled across different experimental setups and aquifers [66]. However, the models used to study particle retention in porous media have certain limitations that should be considered. One limitation is using single-fitting parameters to describe the multiple retention mechanisms. Also, the models depicted in Table 7 only fit specific mechanisms, meaning that accurate modelling of the various mechanisms of nanoparticle retention would require more than one equation, which would require significant computing time and power. A further limitation is the assumption of idealised conditions in the models. Many models assume uniform and homogeneous porous media, neglecting the heterogeneity and complexity of real-world porous media [67]. This simplification may not accurately represent particles' transport and retention behaviour in natural systems. The heterogeneity of porous media can significantly affect particle deposition and retention, and neglecting this aspect can lead to inaccurate predictions [67]. Another limitation is the assumption of favourable colloid/collector interactions in some models. These models may need to adequately capture the behaviour of particles under unfavourable conditions, where significant particle deposition and retention can occur [67].

6. Case Studies on the Controlled Application of Nanoparticles for Remediation

Several real case studies involving different companies and research organisations have demonstrated the application of nanoparticles for use in porous media, especially for remediation purposes. Despite some of the reported successes of these projects, there have been reported challenges concerning controlled emplacement, immobilisation, and long-term stability [62]. Some of the case studies relating to the use of nanoparticles for remediation are given below:

(a) Lockheed Martin—Environmental Remediation Using Nanoparticles
  - Case Study: Lockheed Martin has researched the use of nanoparticles for environmental remediation, focusing on groundwater clean-up. They used iron nanoparticles to degrade contaminants like chlorinated solvents.
  - Challenge: One of the key challenges they faced was ensuring the long-term stability of nanoparticles in the subsurface. Controlling the mobility of nanoparticles to prevent unintended migration and understanding their reactivity over time were critical challenges.

(b) SiREM—NanoRem Project
  - Case Study: SiREM, a Canadian environmental remediation company, participated in the NanoRem project, which aimed to develop innovative nanoremediation solutions for contaminated sites.
  - Challenge: SiREM faced challenges in predicting the long-term stability of nanoparticles in the field and ensuring their effectiveness over extended periods. Environmental conditions, such as changing pH levels and competition with natural organic matter, posed stability challenges.

(c) NanoRem—Collaborative Project
  - Case Study: The NanoRem project, a collaboration of multiple European organisations, focused on applying nanoparticles for groundwater remediation.
  - Challenge: The project addressed the need to assess the long-term stability and potential risks of nanoremediation. They encountered challenges related to regulatory compliance and the need to develop standardised protocols for testing and monitoring.

(d) NANO IRM—French Research Project
  - Case Study: NANO IRM, a French research project, explored the use of nanoparticles for in situ remediation of contaminated groundwater.
  - Challenge: The project emphasised the importance of understanding nanoparticle transport and long-term stability, especially in complex geological settings. Maintaining nanoparticle reactivity and stability over time was a central challenge.

(e) NASA—Nanoparticles for Water Filtration
  - Case Study: NASA conducted research on using nanoparticles for water purification and environmental remediation in space and on Earth.
  - Challenge: NASA's work highlighted the need for long-term stability and durability of nanoparticles in porous media for water purification. Achieving stable nanoparticle behaviour in dynamic and extreme environments was a challenge.

These case studies provide insights into real-world applications of nanoparticles for remediation purposes and the challenges associated with ensuring their long-term stability in porous media. Overall, companies specialising in nanoparticle-based remediation face challenges related to the controlled emplacement and long-term stability of deposited nanoparticles in porous media. These challenges can be broken down into agglomeration, leaching, transport mechanisms, and longevity. As mentioned earlier, potential solutions involve surface modifications, improved encapsulation, nanoparticle design enhancements, real-time monitoring, and in situ maintenance techniques to address these challenges. These proposed solutions would ensure longevity, controlled deposition, and effectiveness of nanoparticle-based remediation strategies.

7. Conclusions and Recommendations

The deployment of nanoparticles in porous media for environmental remediation and other applications presents a promising avenue for addressing contamination and enhancing targeted delivery. However, various complexities and challenges must be addressed to ensure nanoparticle-controlled injection, deposition, and long-term stability. This comprehensive review has highlighted the strategies, factors, and innovative approaches to achieving these goals. Surface modification, smart materials, injection strategies, and in situ monitoring are among the strategies used to control nanoparticle deposition. However, they are met with challenges like uniform modification, injection rate control, and achieving fine-tuned control. Factors influencing nanoparticle stability in porous media include flow velocity, pH, ionic strength, cation type, coating, concentration, and size. Understanding these factors is essential for the success of nanoparticle-based applications. Nanoparticle degradation in porous media can occur due to chemical reactions, coating erosion, agglomeration, biological interactions, physical weathering, electrochemical reactions, changes in environmental conditions, and ageing effects. Managing these mechanisms is critical to ensure nanoparticle longevity. Innovative strategies for maintaining stability, including surface modification, smart nanoparticles, self-healing coatings, encapsulation, and responsive gels, offer potential solutions. However, they must be carefully implemented to overcome their respective limitations. Real-world case studies, like Lockheed Martin's environmental remediation project and collaborative efforts like NanoRem and NANO IRM, provide valuable insights into the application of nanoparticle-based remediation. They underline the importance of understanding long-term stability, regulatory compliance, and the need for standardisation. Based on this, the following recommendations are suggested for future works:

(a) Advanced Characterisation Techniques: Future research should focus on developing advanced characterisation techniques that provide real-time insights into nanoparticle behaviour in porous media. These techniques can help monitor and control nanoparticle distribution more effectively.
(b) Modelling and Simulation: Computational modelling and simulation can be vital in predicting nanoparticle behaviour and optimising their deployment in porous media. These models should consider the complex interplay of factors affecting stability and deposition.
(c) Standardisation and Regulations: Efforts should be made to establish standardised protocols for nanoparticle-based remediation projects. This includes guidelines for controlled application, monitoring, testing, and reporting results. Furthermore, regulatory bodies should work alongside researchers to ensure safe and environmentally responsible nanoparticle deployment.

(d) Green Nanoparticles: Investigate and develop environmentally friendly nanoparticles with minimal ecological impact. This aligns with sustainability goals and can contribute to safer remediation practices.
(e) Nanoparticle Recycling: Explore methods for recovering and recycling nanoparticles after their application in porous media. This can reduce waste and cost while addressing potential concerns about the uncontrolled release of nanoparticles.
(f) Collaborative Research: Encourage interdisciplinary collaboration between researchers, engineers, environmental scientists, and regulatory agencies to address the complex challenges of nanoparticle-based remediation comprehensively.
(g) Long-Term Monitoring: Conduct long-term monitoring of sites where nanoparticles have been applied for remediation to assess their sustained effectiveness and environmental impact.

The controlled application of nanoparticles in porous media is a promising field with the potential to revolutionise environmental remediation and targeted delivery. By addressing the challenges and implementing the recommended strategies, future research can ensure the safe, effective, and sustainable use of nanoparticles in porous media applications, leading to lasting positive impacts on the environment and various industries.

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