BILINGUAL PUBLISHING GROUP

Journal of Environmental & Earth Sciences
https://journals.bilpubgroup.com/index.php/jees

REVIEW

Study on the Impact of Coal Mine Floor Grouting Renovation on the Hydrogeological and Geochemical Characteristics of the Mining Area Aquifer

Zhaopeng Yang [1*]***, Like Wei*** [2]

[1] *North China Institute of Science and Technology, Langfang City 065201, China*

[2] *School of Mine Safety, University of Emergency Management, Langfang City 065201, China*

ABSTRACT

Floor grouting renovation is widely applied in coal mining to control water inrush and enhance the stability of the floor strata. However, its impacts extend beyond engineering performance, significantly influencing the hydrogeological and geochemical characteristics of aquifer systems. This review provides a comprehensive synthesis of current knowledge on the mechanisms, processes, and environmental implications of floor grouting in mining regions. It examines how grouting modifies aquifer permeability, porosity, groundwater flow patterns, and pressure regimes, as well as its effects on groundwater chemistry, including pH, major ions, and trace elements. Particular emphasis is placed on the coupled hydrogeological–geochemical processes that govern system evolution, highlighting the feedback mechanisms between physical and chemical changes. The review also addresses the long-term behavior of grouted aquifers, including the stability of sealing effects and potential delayed impacts on groundwater quality. Environmental implications, such as effects on regional water resources and ecosystems, are critically evaluated. Despite significant progress, existing studies often lack cross-disciplinary integration and long-term perspectives. This review identifies key research gaps and proposes future directions, including the development of eco-friendly materials, advanced monitoring techniques, and coupled modeling approaches. The findings contribute to a more holistic understanding of grouting-induced changes and provide guidance for sustainable and safe coal mining practices.

Keywords: Floor Grouting Renovation; Hydrogeological Characteristics; Groundwater Geochemistry; Coupled Processes; Coal Mining Aquifers

*CORRESPONDING AUTHOR:
Zhaopeng Yang, North China Institute of Science and Technology, Langfang City 065201, China; Email: 742806600@163.com

ARTICLE INFO
Received: 29 May 2026 | Revised: 18 June 2026 | Accepted: 23 June 2026 | Published Online: 14 August 2026
DOI: https://doi.org/10.30564/jees.v8i8.13576

CITATION
Yang, Z., Wei, L., 2026. Study on the Impact of Coal Mine Floor Grouting Renovation on the Hydrogeological and Geochemical Characteristics of the Mining Area Aquifer. Journal of Environmental & Earth Sciences. 8(8): 721–738. DOI: https://doi.org/10.30564/jees.v8i8.13576

1. Introduction

Coal remains a dominant primary energy source in many countries, and its large-scale extraction has inevitably led to increasingly complex hydrogeological challenges [1]. Among these, groundwater inrush and aquifer disturbance are among the most critical threats to both mine safety and regional water resources [2]. In deep coal mining environments, the floor strata underlying coal seams often act as a barrier separating confined aquifers from mining operations. However, due to tectonic activity, lithological heterogeneity, and mining-induced stress redistribution, these floor strata are frequently fractured or weakened, creating potential pathways for high-pressure groundwater to enter mine workings. A conceptual representation of this hydrogeological setting and the role of floor grouting is illustrated in **Figure 1**. Such water inrush events not only endanger personnel and equipment but also disrupt production and cause long-term ecological damage.

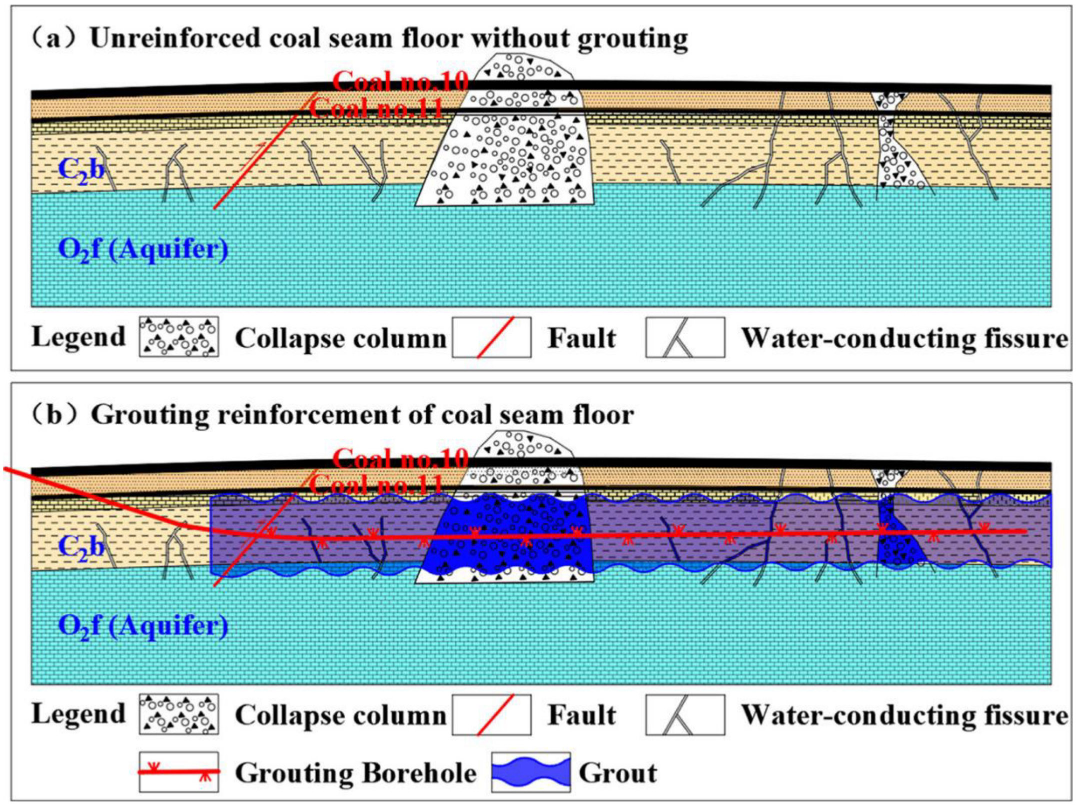

Figure 1. Conceptual diagram of coal mine floor strata showing groundwater inrush pathways and the role of floor grouting in modifying hydraulic connectivity.

To mitigate these risks, floor grouting renovation has become a widely adopted engineering measure in modern coal mining [3,4]. This technique involves injecting grout materials into the fractured or permeable zones of the mine floor to reinforce the rock mass, reduce permeability, and enhance the integrity of aquicludes. Over the past decades, significant progress has been made in the development of grouting materials, injection technologies, and evaluation methods. As a result, floor grouting has proven effective in reducing water inrush hazards and improving the mechanical stability of mining environments. Nevertheless, while the engineering performance of grouting has been extensively studied, its broader impacts on aquifer systems—particularly from hydrogeological and geochemical perspectives—remain insufficiently understood.

From a hydrogeological standpoint, floor grouting renovation alters the physical properties of the subsurface environment in multiple ways. The injection of grout modifies pore structures, seals fractures, and changes the permeability and hydraulic conductivity of the treated zones [5]. These changes can significantly influence groundwater flow regimes, pressure distributions, and hydraulic connectivity between aquifers and mining voids. In some cases, grouting may effectively isolate aquifers and reduce water inflow; in others, it may redirect flow paths or induce pressure buildup in adjacent zones, potentially leading to unintended consequences. Despite the growing body of case studies, there remains a lack of systematic synthesis of how different grouting strategies influence aquifer behavior under varying geological conditions.

Equally important, but far less explored, are the geochemical impacts of floor grouting renovation. Grouting materials ranging from traditional cement-based slurries to modern chemical and composite formulations introduce new reactive substances into the subsurface environment [6,7]. These materials can interact with groundwater and host rocks, triggering a series of geochemical processes, including dissolution, precipitation, ion exchange, and redox reactions. Such interactions may alter groundwater composition, including pH, major-ion concentrations, and trace-element mobility. Under certain conditions, the introduction of alkaline grout materials may increase pH and promote mineral precipitation, whereas under others, it may mobilize potentially harmful elements. Moreover, the long-term evolution of these geochemical processes remains poorly constrained, raising concerns about potential impacts on groundwater quality and ecosystem health.

The complexity of these processes is further amplified by the strong coupling between hydrogeological and geochemical dynamics. Changes in permeability and flow paths induced by grouting can influence solute transport and reaction rates, while geochemical reactions may, in turn, modify pore structures and hydraulic properties [8]. For example, mineral precipitation within fractures can enhance sealing effects, whereas dissolution processes may reopen previously sealed pathways. This bidirectional feedback highlights the need for an integrated perspective that accounts for both physical and chemical processes. However, most existing studies tend to focus on either hydrogeological or geochemical aspects in isolation, resulting in a fragmented understanding of the overall system response.

In addition to scientific challenges, there are pressing practical and environmental considerations. As coal mining operations extend to greater depths and more complex geological settings, the scale and intensity of grouting activities continue to increase. This raises important questions regarding the long-term sustainability of such interventions, particularly in regions where groundwater resources are scarce or serve as critical sources of drinking water and agricultural supply. Understanding how grouting affects aquifer systems is therefore essential not only to ensure mining safety but also to protect regional water environments and achieve sustainable resource development [9,10].

Against this background, the present review aims to provide a comprehensive and integrated analysis of the impacts of coal mine floor grouting renovation on the hydrogeological and geochemical characteristics of aquifers in the mining area. Unlike previous studies that primarily emphasize engineering effectiveness or short-term hydrogeological responses, this review highlights the coupled processes governing aquifer evolution following grouting interventions. It systematically synthesizes existing knowledge on how grouting modifies aquifer structure, groundwater flow, and chemical composition, and it critically evaluates the interactions between these processes [11].

Despite extensive research on floor grouting renovation, three critical knowledge gaps persist in the existing literature. First, most studies focus on either hydrogeological or geochemical impacts in isolation, neglecting the coupled feedback mechanisms between physical and chemical changes. Second, the long-term evolution of grouted aquifer systems—beyond immediate post-grouting effects—remains poorly constrained. Third, a systematic synthesis linking grouting strategies to both engineering performance and environmental outcomes is lacking.

To address these gaps, the present review provides a comprehensive and integrated analysis of the impacts of coal mine floor grouting renovation on aquifer systems. The novelty of this review is threefold. It adopts a coupled-process perspective that explicitly examines bidirectional interactions between permeability changes and geochemical reactions, rather than treating the two domains separately. It incorporates a temporal dimension that distinguishes immediate, short-term, and long-term effects, including delayed responses such as pressure buildup and grout degradation. It also integrates multi-scale evidence from laboratory experiments, field observations, and numerical modeling to provide a cross-scale understanding from pore-level reactions to aquifer-scale flow redistribution. The findings are intended to guide more sustainable grouting practices, inform environmental risk assessments, and support regulatory decision-making for coal mining operations in water-sensitive regions.

The novelty of this review lies in three key aspects. First, it bridges the gap between hydrogeological and geochemical perspectives by examining their coupled mechanisms, rather than treating them as independent domains [12]. Second, it emphasizes the temporal dimension of grouting impacts, considering not only immediate effects but also long-term evolution and potential delayed responses in aquifer systems [11]. Third, it integrates insights from laboratory experiments, field observations, and numerical modeling to provide a multi-scale understanding of grouting-induced changes [13]. By doing so, the review offers a more holistic framework for evaluating the effectiveness and environmental implications of floor grouting renovation.

Ultimately, this work seeks to advance the scientific understanding of subsurface processes associated with coal mining and to inform the development of more sustainable and environmentally responsible grouting practices. The findings are expected to be of interest to researchers and practitioners in hydrogeology, geochemistry, mining engineering, and environmental science, and to serve as a valuable reference for future studies and engineering applications.

2. Mechanisms and Technologies of Floor Grouting Renovation

2.1. Fundamental Mechanisms of Floor Grouting in Coal Mines

Floor grouting renovation is fundamentally a process of modifying the physical structure and hydraulic behavior of the coal seam floor to enhance its resistance to groundwater inflow [14]. At its core, the technique involves injecting fluid or semi-fluid materials into fractured or porous rock masses, where they subsequently diffuse, penetrate, and solidify. This process leads to the filling of voids, sealing of fractures, and bonding of loose particles, thereby reducing permeability and increasing the mechanical strength of the treated strata.

The governing mechanisms of grout migration are controlled by a combination of hydro-mechanical factors, including injection pressure, rock permeability, fracture aperture, and in situ stress conditions. In low-permeability media, grout tends to propagate along pre-existing fractures or weak planes, often forming anisotropic diffusion patterns. Conversely, in highly fractured zones, grout may exhibit more complex flow behavior, including branching and preferential channeling. The interplay between grout rheology and the hydrogeological properties of the host rock is therefore critical in determining the spatial distribution and effectiveness of the treatment [15]. From a hydrogeological perspective, the primary objective of floor grouting is to disrupt hydraulic connectivity between aquifers and mining voids. This is achieved by reducing the transmissivity of the floor strata and increasing the effective thickness of the aquiclude. However, this process is not merely a passive sealing operation. The injection of grout can induce stress redistribution within the rock mass, potentially leading to fracture closure in some regions and fracture propagation in others. Such dual effects highlight the need for a nuanced understanding of the coupled hydro-mechanical processes involved [16].

2.2. Grouting Materials and Their Properties

The selection of grouting materials plays a pivotal role in determining both the engineering performance and environmental impact of floor grouting renovation. Traditionally, cement-based grouts have been the most widely used due to their availability, cost-effectiveness, and relatively straightforward handling. These materials typically consist of Portland cement mixed with water and various additives to control setting time, viscosity, and strength development. While effective in filling larger fractures and voids, their relatively high viscosity can limit penetration into fine fissures, thereby reducing their sealing efficiency in low-permeability formations [17].

To address these limitations, chemical grouts have been developed, including silicate-based, polymer-based, and resin-based formulations. These materials are characterized by lower viscosity and better injectability, allowing them to penetrate finer pore spaces and microfractures [18]. However, their application is often constrained by higher costs, potential toxicity, and sensitivity to environmental conditions such as temperature and pH. Composite grouting systems, which combine cementitious and chemical components, have emerged as a promising alternative, offering a balance between penetration capability and mechanical strength.

Despite these advancements, the long-term stability of grouting materials remains a critical concern. Cement-based grouts may undergo chemical alteration when exposed to groundwater, leading to processes such as leaching, carbonation, or sulfate attack [19]. Similarly, certain chemical grouts may degrade over time or release secondary contaminants into groundwater [20]. These issues underscore the importance of considering not only the immediate engineering requirements but also the long-term geochemical compatibility between grout materials and the surrounding environment. The main types of grouting materials, along with their properties, advantages, and environmental considerations, are summarized in **Table 1**.

Table 1. Summary of commonly used grouting materials, their properties, engineering performance, and environmental considerations.

Grouting Material Type	Main Components	Main Properties	Advantages	Limitations	Environmental Considerations
Cement-based grout	Portland cement, water, additives	High strength, high viscosity	Cost-effective, widely available	Limited penetration in fine fractures	May increase pH, potential leaching
Chemical grout (silicate)	Sodium silicate, reactants	Low viscosity, fast setting	Good injectability, deep penetration	Lower strength, sensitive to conditions	Possible groundwater contamination
Polymer grout	Acrylics, polyurethane	Adjustable viscosity, flexible	High sealing efficiency	Expensive, complex handling	Potential toxicity concerns
Composite grout	Cement + chemical additives	Balanced properties	Improved penetration and strength	Design complexity	Depends on formulation
Eco-friendly grout	Modified cement, bio-based additives	Reduced chemical impact	Environmentally safer	Limited field validation	Lower ecological risk

2.3. Grouting Techniques and Engineering Implementation

The effectiveness of floor grouting renovation depends heavily on the techniques used during implementation. Grouting operations typically involve drilling boreholes into the target strata, followed by the controlled injection of grout under specified pressure and flow conditions. The design of the borehole layout, including spacing, depth, and orientation, is crucial for achieving adequate coverage and ensuring uniform treatment [21].

Pressure control is a key parameter in grouting operations. Insufficient pressure may result in limited grout penetration, while excessive pressure can induce hydraulic fracturing, potentially creating new pathways for groundwater flow [22]. The optimal pressure range is therefore site-specific and must be carefully determined based on geological conditions and grout properties. In recent years, the use of staged or segmented grouting techniques has gained attention, allowing for more precise control over grout distribution and reducing the risk of over-injection. Advancements in monitoring and control technologies have also enhanced the effectiveness of grouting operations. Real-time monitoring of injection pressure, flow rate, and grout volume provides valuable feedback for adjusting operational parameters. Geophysical methods, such as electrical resistivity tomography and acoustic emission monitoring, have been increasingly used to track grout diffusion and assess the extent of treated zones. These techniques contribute to a more informed and adaptive approach to grouting, reducing uncertainties and improving overall performance.

Nevertheless, significant challenges remain in the practical implementation of grouting technologies. Geological heterogeneity, including variations in lithology, fracture density, and stress conditions, can lead to uneven grout distribution and unpredictable outcomes [15]. In addition, the scale of mining operations often necessitates large volumes of grout, raising logistical and economic concerns. These challenges highlight the need for more sophisticated design methodologies that integrate geological characterization with engineering optimization.

2.4. Evaluation and Optimization of Grouting Effectiveness

Assessing the effectiveness of floor grouting renovation is essential for both ensuring mine safety and guiding future operations. Traditional evaluation methods primarily rely on indirect indicators, such as reductions in water inflow rates, changes in hydraulic pressure, and improvements in rock strength [21]. While these metrics provide useful information, they often lack spatial resolution and may not fully capture the complexity of subsurface processes.

More advanced evaluation approaches have been developed to address these limitations. Hydraulic testing, including packer tests and pumping tests, can provide quantitative estimates of permeability changes before and after grouting [23]. Tracer experiments offer insights into flow paths and connectivity, enabling a more detailed understanding of how grouting alters groundwater movement. In addition, numerical modeling has become an increasingly important tool for simulating grout diffusion and predicting its impact on hydrogeological systems.

A critical issue in evaluating grouting effectiveness is the distinction between short-term and long-term performance [6]. Immediately after grouting, permeability reductions may appear significant; however, these effects can diminish over time due to mechanical relaxation, chemical alteration, or the development of new fractures. Long-term monitoring is therefore essential for assessing the durability of grouting interventions. Despite this, many existing studies are limited to short observation periods, resulting in an incomplete understanding of the temporal evolution of treated systems.

Optimization of grouting strategies requires a comprehensive approach that integrates material selection, injection design, and performance evaluation. Increasingly, researchers are exploring the use of coupled hydro-mechanical and geochemical models to simulate the complex interactions involved in grouting processes. Such models have the potential to improve predictive capabilities and support more efficient and environmentally sustainable practices. However, their application remains constrained by uncertainties in parameter estimation and the difficulty of validating model results against field data [24].

In summary, while significant progress has been made in the development of floor grouting technologies, there remains a need for more integrated and systematic approaches. Future advancements will likely depend on the ability to combine detailed geological characterization with innovative materials, precise engineering techniques, and robust evaluation frameworks. Only through such multidisciplinary efforts can the full potential of floor grouting renovation be realized in addressing the hydrogeological challenges of modern coal mining [11].

3. Impact on Hydrogeological Characteristics of Aquifers

3.1. Modification of Aquifer Permeability and Porosity

Floor grouting renovation fundamentally alters the intrinsic hydraulic properties of aquifer systems, particularly permeability and porosity, which govern groundwater storage and flow behavior [11]. The injection of grout into the fractured floor strata leads to the partial or complete filling of void spaces, effectively reducing the interconnected pore network. This process is especially pronounced in fractured aquifers where permeability is dominated by fracture apertures rather than matrix porosity. By sealing these preferential pathways, grouting can significantly decrease hydraulic conductivity and enhance the integrity of aquicludes separating mining zones from underlying aquifers.

However, permeability modification is rarely uniform. Due to geological heterogeneity, grout distribution tends to be spatially variable, resulting in anisotropic hydraulic properties after treatment. In zones where fractures are well-connected and accessible, permeability reduction may be substantial, whereas in poorly connected or low-permeability zones, grout penetration may be limited. This uneven alteration can create residual high-permeability channels, which may continue to act as conduits for groundwater flow. Consequently, the overall effectiveness of grouting in reducing aquifer permeability depends not only on the volume of grout injected but also on the degree of connectivity within the fracture network [15].

Porosity changes induced by grouting are similarly complex. While primary porosity is reduced through void filling, secondary porosity may evolve due to stress redistribution and geochemical reactions. For instance, grout injection can induce compaction or closure of microfractures under increased stress, further decreasing porosity. Conversely, in some cases, hydraulic fracturing caused by excessive injection pressure may generate new void spaces, temporarily increasing porosity and potentially offsetting the intended sealing effect. These competing processes highlight the dynamic nature of aquifer property modification during and after grouting [25].

3.2. Alterations in Groundwater Flow Patterns and Hydraulic Connectivity

One of the most significant hydrogeological impacts of floor grouting is the alteration of groundwater flow regimes [14]. Reducing permeability in targeted grouting disrupts existing flow paths and modifies the spatial distribution of hydraulic gradients. This can lead to a redistribution of groundwater flow, often diverting it away from mining zones and thereby reducing the risk of water inflow. In ideal scenarios, grouting creates an effective hydraulic barrier that isolates the mining area from high-pressure aquifers.

Nevertheless, the reconfiguration of flow patterns can produce unintended consequences. When flow paths are obstructed, groundwater may seek alternative routes, potentially activate previously inactive flow regions, or enhance flow through adjacent strata. This redirection can increase hydraulic pressure in untreated zones, raising the risk of localized water inrush events outside the grouted area. Such phenomena are particularly relevant in complex geological settings where multiple aquifers and fault systems interact [26].

Hydraulic connectivity between aquifers is also significantly influenced by grouting activities. In many mining regions, vertical or inclined fractures serve as conduits linking different aquifer layers. Grouting can reduce or eliminate these connections, effectively compartmentalizing the groundwater system. While this isolation is beneficial for mine safety, it may disrupt natural groundwater circulation and affect regional water balance. In some cases, reduced connectivity can lead to groundwater stagnation, altering recharge-discharge dynamics and potentially impacting water quality [22].

The extent to which grouting modifies flow patterns depends on several factors, including the scale of treatment, the initial hydrogeological conditions, and the properties of the injected grout [15]. Despite numerous case studies, there remains a lack of generalized frameworks for predicting flow redistribution following grouting. This limitation underscores the need for integrated hydrogeological modeling that accounts for both pre-existing conditions and post-treatment changes.

3.3. Influence on Aquifer Pressure Regimes and Water Inrush Risk

Aquifer pressure is a critical parameter in assessing the risk of groundwater inrush in coal mining operations [2]. Floor grouting directly influences pressure regimes by altering the transmissivity and storage properties of the aquifer system. By reducing permeability, grouting can limit the transmission of hydraulic pressure to mining voids, thereby lowering the likelihood of sudden water inflow. This pressure attenuation effect is often considered a primary indicator of grouting success.

However, the relationship between grouting and pressure dynamics is not always straightforward. In confined aquifers, the reduction of permeability may lead to pressure buildup upstream of the treated zone. If this pressure is not adequately relieved, it can increase the potential for hydraulic failure in adjacent or untreated areas. Such pressure accumulation may also reactivate dormant fractures or faults, creating new risk pathways for water inrush [27].

Temporal variations in pressure further complicate the assessment. Immediately after grouting, pressure levels may decrease due to reduced flow to the mining area. Over time, however, pressure may gradually recover or even exceed pre-grouting levels as the aquifer system adjusts to the new hydraulic conditions [11]. This delayed response highlights the importance of long-term monitoring in evaluating the effectiveness and safety of grouting interventions. Moreover, the interaction between mining-induced stress changes and grouting effects can influence pressure distribution. Excavation activities often lead to stress redistribution, which may either enhance or counteract the effects of grouting. For example, stress concentration near the mining face may cause fracture closure, complementing the sealing effect of grout [28]. Conversely, stress relief in certain zones may promote fracture opening, undermining the stability of the grouted barrier. Understanding these coupled processes is essential for accurately predicting water inrush risk.

3.4. Evolution of Fracture Networks and Sealing Performance

Fracture networks play a dominant role in controlling groundwater movement in many coal-bearing formations [29]. Floor grouting directly targets these networks, aiming to reduce their connectivity and hydraulic efficiency. The injection of grout into fractures seals them, partially or completely, enhancing the overall impermeability of the rock mass. The effectiveness of this sealing process depends on fracture geometry, aperture size, and connectivity, as well as the rheological properties of the grout. The evolution of fracture networks during grouting is influenced by both mechanical and hydraulic factors. Injection pressure can induce deformation of fracture walls, leading to either closure or propagation. When pressure exceeds the rock's tensile strength, new fractures may form, altering the original network structure. These newly formed fractures may initially serve as additional pathways for grout migration, but they can also become potential leakage channels if not fully sealed.

Post-grouting, fracture networks continue to evolve under the influence of in situ stress and groundwater flow [30]. Over time, mechanical relaxation may cause previously sealed fractures to reopen, particularly in areas under cyclic loading or other mining disturbances. Additionally, geochemical processes such as mineral precipitation or dissolution can modify fracture apertures, either enhancing or reducing sealing effectiveness. For instance, the precipitation of secondary minerals within fractures may strengthen the grout-rock interface, whereas dissolution processes may weaken it.

The long-term stability of sealing performance is therefore a critical issue [17]. While short-term results often indicate significant reductions in permeability, maintaining these effects over extended periods remains challenging. Field observations have shown that the durability of grouting treatments can vary widely depending on site-specific conditions. This variability highlights the need for a better understanding of fracture evolution and for the development of more resilient grouting materials and techniques.

3.5. Monitoring and Characterization of Hydrogeological Changes

Accurate monitoring and characterization of hydrogeological changes are essential for evaluating the impact of floor grouting on aquifer systems [31]. Traditional monitoring approaches, such as measuring water inflow rates and hydraulic heads, provide valuable but limited information. These methods often lack the spatial resolution needed to capture subsurface changes in heterogeneity and may not fully capture the complexity of flow redistribution.

Advances in monitoring technologies have significantly improved the ability to characterize hydrogeological responses to grouting. Geophysical methods, including electrical resistivity tomography, seismic surveys, and ground-penetrating radar, enable non-invasive imaging of subsurface structures and grout distribution [32]. These techniques can reveal the extent of treated zones and identify areas where grouting may be incomplete or ineffective.

Hydraulic testing methods, such as packer tests and tracer experiments, offer more direct insights into changes in permeability and flow paths. Tracer studies, in particular, are useful for identifying connectivity between aquifers and assessing the effectiveness of sealing feet. When combined with numerical modeling, these data can provide a comprehensive understanding of aquifer behavior before and after grouting.

Despite these advancements, challenges remain in integrating diverse data types and interpreting results in complex geological settings. Monitoring systems are limited by practical constraints, including cost, accessibility, and the scale of mining operations [33]. Furthermore, many studies focus on short-term observations, which limit the ability to assess long-term hydrogeological evolution. A critical gap in current research is the lack of standardized methodologies for monitoring and evaluating grouting impacts. The development of integrated monitoring frameworks that combine multiple techniques and extend over longer time scales is essential for improving the reliability of assessments. Such approaches would not only enhance understanding of hydrogeological changes but also support the optimization of grouting strategies and the sustainable management of groundwater resources. A summary of the major hydrogeological impacts of floor grouting on aquifer systems is presented in **Table 2**.

Table 2. Summary of hydrogeological changes induced by floor grouting and their associated mechanisms and risks.

Hydrogeological Parameter	Pre-Grouting Condition	Post-Grouting Change	Mechanism	Potential Risks
Permeability	High in fractured zones	Significant reduction	Fracture filling, sealing	Uneven distribution, residual pathways
Porosity	Controlled by fractures and matrix	Decrease or localized increase	Void filling or induced fracturing	Secondary porosity formation
Groundwater flow	Established natural flow paths	Flow redirection or blockage	Hydraulic barrier formation	Flow diversion to untreated zones
Hydraulic connectivity	Connected aquifers	Partial or full isolation	Sealing of contact pathways	Disruption of natural recharge
Aquifer pressure	Natural or mining-affected	Redistribution or buildup	Reduced transmissivity	Pressure accumulation, failure risk

4. Impact on Geochemical Characteristics of Groundwater

4.1. Changes in Groundwater Chemistry and Hydrochemical Facies

Floor grouting renovation introduces substantial perturbations to the geochemical equilibrium of aquifer systems, often leading to measurable changes in groundwater chemistry [34]. One of the most immediate effects is the alteration of hydrochemical facies, driven by interactions between injected grout materials and native groundwater [35]. Cement-based grouts, which are typically alkaline, can significantly increase groundwater pH upon contact, particularly in confined aquifers with limited buffering capacity. This shift toward alkaline conditions may subsequently influence the solubility and mobility of various ions and minerals.

Changes in major ion composition are commonly observed following grouting activities. Elevated concentrations of calcium and hydroxide ions are often associated with the dissolution of cementitious materials, whereas reductions in bicarbonate levels may result from the precipitation of carbonate minerals. In some cases, sulfate concentrations may increase due to interactions between grout additives and sulfate-bearing minerals in the host rock. These chemical changes can lead to a transition in hadrochemical facies, for example, from bicarbonate-dominated to sulfate- or hydroxide-dominated water types [19].

The extent and persistence of these changes depend on several factors, including the volume and composition of the injected grout, the residence time of groundwater, and the degree of mixing between treated and untreated zones [36]. In highly dynamic aquifer systems, dilution and natural groundwater flow may mitigate chemical alterations over time. However, in low-permeability or compartmentalized systems, chemical anomalies may persist for extended periods, potentially affecting groundwater usability. Despite numerous case-specific observations, a comprehensive understanding of how grouting influences hadrochemical facies across different geological settings remains limited.

4.2. Water–Rock–Grout Interactions

The geochemical evolution of groundwater following grouting is governed by complex interactions among water, rock, and grout materials [20]. These interactions involve a range of processes, including dissolution, precipitation, ion exchange, and adsorption, which collectively determine the chemical composition of the aquifer system. The introduction of grout materials effectively introduces a new reactive phase that alters the balance of geochemical reactions. Dissolution of grout components is often the initial process following injection. For example, calcium hydroxide and other alkaline phases in cement-based grouts readily dissolve in groundwater, releasing ions that can react with dissolved carbon dioxide to form carbonate minerals. This process not only modifies groundwater chemistry but also contributes to the gradual hardening and stabilization of the grout. At the same time, the dissolution of host rock minerals, such as carbonates or silicates, may be enhanced or suppressed depending on changes in pH and ionic strength.

Precipitation reactions play a crucial role in the long-term evolution of the system. The formation of secondary minerals, such as calcite, gypsum, or silica phases, can result from grout–water-induced supersaturation [37]. These precipitates may accumulate within pore spaces and fractures, further reducing permeability and reinforcing the sealing effect of grouting. However, excessive precipitation may also lead to clogging of flow pathways, altering groundwater movement, and potentially causing localized pressure changes.

Ion exchange and adsorption processes add another layer of complexity. Clay minerals and other active surfaces within the aquifer can exchange cations with the surrounding environment, influencing the distribution of cations such as sodium, calcium, and magnesium [38]. The presence of grout-derived ions may disrupt existing equilibrium conditions, leading to shifts in exchangeable ion compositions. These processes are often reversible and can evolve over time as the system approaches a new steady state. Overall, water-rock grout interactions are highly site-specific and depend on the mineralogical characteristics of both the aquifer and the grout. While laboratory experiments have provided valuable insights into individual reactions, scaling these findings to field conditions remains challenging due to the inherent heterogeneity of subsurface environments. The key water-rock grout interaction pathways and associated reactions are illustrated in **Figure 2**.

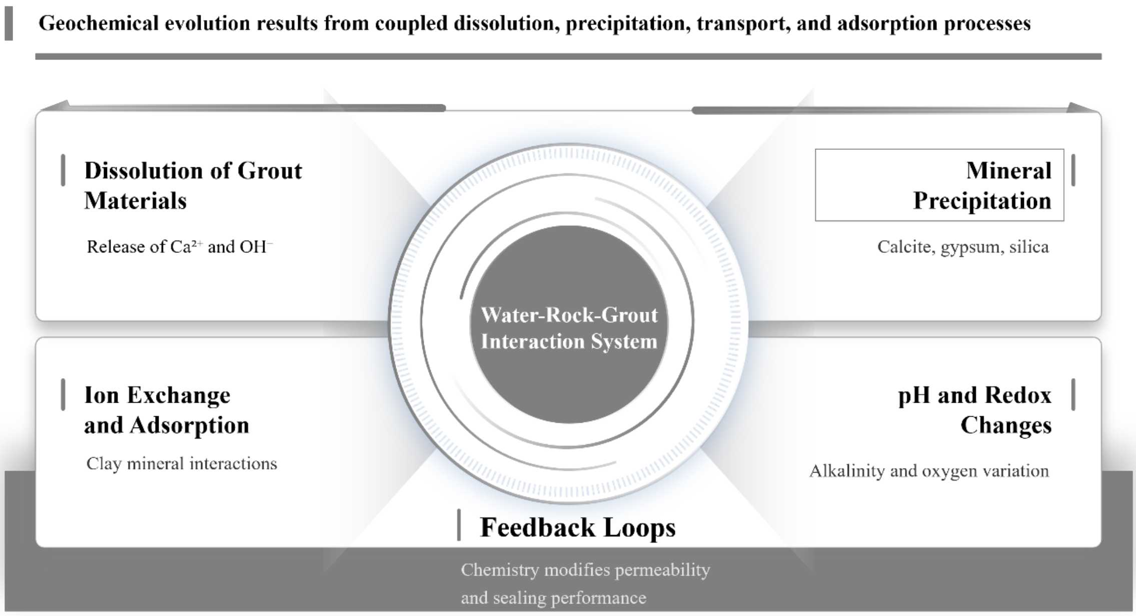

Figure 2. Schematic representation of water–rock–grout interactions, including dissolution, precipitation, ion exchange, and their influence on groundwater chemistry.

4.3. Influence on pH, Redox Conditions, and Mineral Stability

Among the various geochemical parameters affected by floor grouting, pH and redox conditions are particularly significant due to their central role in controlling mineral stability and element mobility [21]. The injection of alkaline grouts typically results in a rapid increase in groundwater pH, often exceeding 10 in the immediate vicinity of the treated zone. This high pH environment can drastically alter the solubility of minerals and the speciation of dissolved elements. Elevated pH conditions generally promote the precipitation of carbonate and hydroxide minerals, thereby enhancing grouting efficiency by filling remaining pore spaces. However, high pH can also destabilize certain minerals, such as aluminosilicates, leading to their dissolution and the release of silica and aluminum into solution. These processes may have secondary effects on groundwater composition and the structural integrity of the rock matrix.

Redox conditions may also be affected, although the mechanisms are often less direct than those governing pH changes. The introduction of grout materials can affect oxygen availability and microbial activity, which play important roles in redox processes. For example, reduced permeability may limit the amount of oxygenated water, leading to more reducing conditions in isolated zones. Conversely, certain chemical grouts may contain oxidizing agents that temporarily alter redox states [39].

Changes in redox conditions can significantly affect the mobility of redox-sensitive elements such as iron, manganese, and arsenic [40]. Under reducing conditions, these elements may become more soluble and mobile, potentially leading to localized contamination. Conversely, oxidizing conditions may promote their precipitation and immobilization. The interplay between pH and redox conditions thus creates a dynamic chemical environment in which mineral stability and element transport are continuously evolving. Understanding these processes is critical for predicting the long-term geochemical behavior of aquifer systems subjected to grouting. However, the complexity of coupled reactions and the influence of site-specific factors make it difficult to develop generalized predictive models.

4.4. Mobilization and Attenuation of Trace Elements and Contaminants

The impact of floor grouting on trace elements and potential contaminants is a growing concern, particularly in regions where groundwater is a critical resource for drinking and agriculture. Grouting activities can influence the mobility of trace elements through both direct and indirect mechanisms. Directly, grout materials may contain trace constituents that are released into groundwater during dissolution. Indirectly, changes in pH, redox conditions, and ionic strength can alter the solubility and adsorption behavior of naturally occurring. For instance, elevated pH conditions associated with cement-based grouts may reduce the mobility of certain heavy metals by promoting their precipitation as hydroxides or carbonates. This can be beneficial for immobilizing contaminants. However, the same conditions may increase the solubility of other elements, such as arsenic or selenium, particularly under specific redox states. Similarly, the presence of competing ions introduced by grout can displace adsorbed contaminants from mineral surfaces, enhancing their transport [19].

Attenuation processes, including adsorption, precipitation, and dilution, play a key role in controlling the spread of contaminants [41]. The formation of secondary minerals can sequester trace elements, and while adsorption onto clay minerals and iron oxides can further reduce their mobility. Over time, these processes may lead to the stabilization of groundwater quality, even in the presence of initial perturbations caused by grouting. Despite these natural attenuation mechanisms, considerable uncertainty remains about the long-term fate of trace elements in grouted aquifer systems. Most studies focus on short-term changes and may not capture delayed release or transformation processes. Furthermore, the variability in grout composition and geological conditions makes it difficult to generalize findings across different sites. This highlights the need for more comprehensive and long-term investigations into the geochemical impacts of grouting.

The major geochemical changes associated with floor grouting are summarized in **Table 3**.

Table 3. Summary of geochemical changes in groundwater induced by floor grouting and their controlling processes.

Geochemical Parameter	Typical Change after Grouting	Driving Process	Implications
pH	Increase (alkaline conditions)	Cement dissolution	Mineral precipitation, altered solubility
Major ions (Ca^{2+}, OH^-)	Increase	Grout-water interaction	Change hydrochemical facies
Sulfate (SO_4^{2-})	Variable (increase or decrease)	Mineral reactions, additives	Potential scaling or corrosion
Trace elements (As, Fe, Mn)	Mobilization or immobilization	pH/redox changes	Water quality risks
Dissolved inorganic carbon	changes	Carbonation reactions	Calcite precipitation
Redox conditions	Local shifts	Oxygen availability, reactions	Element mobility changes

4.5. Isotopic and Geochemical Tracing Techniques

To better understand the geochemical impacts of floor grouting, a range of isotopic and geochemical tracing techniques has been employed. These methods provide valuable tools for identifying solute sources, tracking groundwater movement, and elucidating reaction pathways. Stable isotopes of elements such as hydrogen, oxygen, carbon, and sulfur are commonly used to distinguish between different water sources and to assess mixing processes between grouted and unrouted zones [42].

For example, carbon isotopes can be used to distinguish the origin of dissolved inorganic carbon (DIC) from grout dissolution versus natural carbonate dissolution [43]. Similarly, sulfur isotopes can help identify the sources of sulfate, whether derived from grout additives or from the oxidation of sulfide minerals in the host rock. These isotopic signatures provide insights into the relative contributions to the observed groundwater chemistry. Geochemical modeling, often coupled with isotopic data, enables quantitative simulation of water–rock–grout interactions. Such models can predict the evolution of chemical species over time and help identify dominant reaction mechanisms. When calibrated with field data, they offer a powerful means of assessing the impacts of grouting under different scenarios.

However, the application of tracing techniques is not without limitations. Isotopic signals may be influenced by multiple overlapping processes, making interpretation challenging. Additionally, the cost and technical requirements of isotopic analysis may limit their use in large-scale monitoring programs. Despite these challenges, tracing techniques remain indispensable for advancing the understanding of geochemical processes in grouted aquifer systems [44].

5. Coupled Hydrogeological–Geochemical Processes and Environmental Implications

5.1. Coupling Mechanisms between Physical and Chemical Changes

The impacts of floor grouting renovation on aquifer systems cannot be fully understood without considering the strong coupling between hydrogeological and geochemical processes. Grouting simultaneously alters the subsurface's physical structure and introduces reactive materials, creating a dynamic system in which flow, transport, and chemical reactions interact continuously. This coupling is particularly evident in fractured aquifers, where fluid flow pathways are highly sensitive to both mechanical and chemical changes. From a mechanistic perspective, hydrogeological changes, such as reductions in permeability and modifications to flow paths, directly influence the transport of dissolved species. Slower groundwater velocities in grouted zones can increase residence time, thereby enhancing the extent of water–rock–grout interactions. This prolonged contact facilitates dissolution and precipitation reactions, which in turn may further modify pore structures. For instance, the precipitation of secondary minerals within fractures can further reduce permeability, reinforcing the sealing effect initiated by grouting [5].

Conversely, geochemical processes can significantly influence hydrogeological properties. Dissolution of minerals, whether from grout or host rock, may enlarge pore spaces or reopen previously sealed fractures, thereby increasing permeability. This feedback loop demonstrates that the hydrogeological effectiveness of grouting is not solely determined at the time of injection but evolves over time as geochemical reactions proceed. The interplay between these processes often results in nonlinear system behavior, making prediction and control particularly challenging [34].

Furthermore, the coupling extends to mechanical aspects. Chemical reactions can alter the strength and stiffness of the rock–grout matrix, affecting its response to in situ stresses. For example, mineral precipitation may strengthen fracture fillings, while chemical degradation of grout materials may weaken them. These changes can influence fracture stability and, consequently, groundwater flow. The integration of hydrogeological, geochemical, and mechanical processes thus forms a complex, interdependent system that requires holistic investigation [16].

5.2. Long-Term Evolution of Aquifer Systems after Grouting

While the immediate effects of floor grouting are often well documented, the long-term evolution of aquifer systems remains less understood but critically important. Over extended timescales, the initial conditions established by grouting undergo gradual changes due to ongoing physical and chemical processes. These include stress redistribution, groundwater flow adjustment, and continued geochemical reactions. One of the key aspects of long-term evolution is the stability of permeability reduction. Although grouting may initially achieve significant decreases in hydraulic conductivity, these effects may diminish over time. Mechanical phenomena such as creep, tension relaxation, and mining-induced disturbances can lead to the reopening of fractures or the formation of new ones. Simultaneously, geochemical processes such as dissolution of grout material or the change of secondary minerals can alter the composition of the treated zone. Groundwater chemistry also evolves over time as the system approaches a new equilibrium. The high pH conditions induced by cement-based grouts may gradually decrease as reactions with carbon dioxide and surrounding minerals occur. Similarly, concentrations of dissolved ions introduced during grouting may decline due to dilution, precipitation, or adsorption. However, in confined or poorly connected aquifers, these changes may proceed slowly, leading to prolonged deviations from baseline conditions [20,45].

Another important consideration is the potential for delayed or secondary effects. For example, the accumulation of pressure in an isolated area may eventually weaken the surrounding rock, resulting in sudden hydraulic failure. Likewise, gradual changes in geochemical conditions may mobilize trace elements at later stages, even if initial impacts appear minimal. These delayed responses highlight the importance of long-term monitoring and predictive modeling in assessing the sustainability of grouting interventions [46].

Overall, the long-term evolution of aquifer systems after grouting is characterized by a transition from an engineered state to a new quasi-natural equilibrium. Understanding this transition requires not only detailed field observations but also the development of models that can capture the coupled processes governing system behavior over extended periods.

5.3. Impacts on Regional Groundwater Quality and Ecosystem Health

Beyond the immediate vicinity of mining operations, floor grouting can have broader implications for regional groundwater systems and associated ecosystems [14]. Changes in hydrogeological connectivity and groundwater flow patterns may alter recharge-discharge relationships, potentially affecting the availability of water resources in the surrounding area. For instance, the isolation of aquifers through grouting may reduce natural recharge rates or disrupt connections with surface water bodies, leading to changes in water levels and flow regimes.

Geochemical alterations induced by grouting can also propagate beyond the treated zone, particularly in systems with active groundwater circulation. Elevated pH levels, changes in ion composition, and the presence of trace elements may influence water quality over larger spatial scales. In regions where groundwater is used for drinking or irrigation, such changes may have direct implications for human health and agricultural productivity. Ecosystems that rely on groundwater, such as wetlands and fed habitats, are particularly sensitive to these changes. Variations in groundwater chemistry and flow can affect soil properties, vegetation patterns, and the distribution of aquatic organisms. For example, increased alkalinity may alter nutrient availability, while changes in redox conditions can impact microbial communities and biogeochemical cycles. These ecological responses are often complex and may not be immediately apparent, requiring integrated approaches that consider both hydrological and biological factors [47].

It is important to note that the magnitude of these impacts depends on the scale and characteristics of the grouting operations. In some cases, the effects may be localized and transient, whereas in others, they may extend over considerable distances and persist for long durations. Despite growing awareness of these issues, there remains a lack of comprehensive studies linking grouting activities to regional environmental outcomes. This gap underscores the need for multidisciplinary research that integrates hydrogeology, geochemistry, and ecology [46] .

5.4. Risk Assessment and Environmental Management Strategies

Given the potential environmental implications of floor grouting, systematic risk assessment and management strategies are essential for ensuring sustainable mining practices [9]. Risk assessment involves the identification, evaluation, and prioritization of potential adverse effects associated with grouting activities. This requires a thorough understanding of site-specific conditions, including geological structure, hydrogeological characteristics, and baseline groundwater quality.

One of the chief challenges in risk assessment is the inherent uncertainty associated with subsurface systems. The heterogeneity of geological formations and the complexity of coupled processes make it difficult to predict outcomes with high confidence [15]. Probabilistic approaches and scenario analysis are increasingly used to evaluate potential risks under different conditions. These methods allow for the consideration of multiple variables and help identify critical factors influencing system behavior.

Environmental management strategies aim to mitigate identified risks and optimize the benefits of grouting. Material selection is a key aspect, with increasing emphasis on environmentally friendly grouts that minimize chemical impacts. In engineering design, can also be optimized to reduce over-injection and limit the extent of disturbance to aquifer systems. In addition, implementing real-time monitoring systems enables adaptive management, allowing timely adjustments based on observed conditions. Long-term monitoring programs are particularly important for assessing the effectiveness of management measures and detecting delayed impacts. These programs should include both hydrogeological and geochemical parameters, as well as, where appropriate, ecological indicators. Data obtained from monitoring can inform model refinement and improve future decision-making [31].

Despite these advancements, challenges remain in translating scientific understanding into practical guidelines. Regulatory frameworks may vary across regions, and there is often a lack of standardized criteria for evaluating grouting impacts. Bridging this gap requires collaboration between researchers, industry practitioners, and policymakers to develop comprehensive and consistent management approaches.

5.5. Modeling Approaches for Coupled Processes

Modeling plays a crucial role in advancing the understanding of coupled hydrogeological and geochemical processes associated with floor grouting [46]. Numerical models provide a means of integrating diverse data sets and simulating system behavior under various scenarios. These models range from relatively simple analytical solutions to highly complex dimensional simulations that incorporate multiple interacting processes.

Coupled hydrogeological–geochemical models typically integrate groundwater flow equations with solute transport and reaction kinetics. Such models can simulate the diffusion of grout, the evolution of permeability, and the evolution of groundwater chemistry over time. When extended to include mechanical processes, these models become hydro-mechanical–chemical (HMC) frameworks capable of capturing the full range of interactions occurring in grouted systems [24].

One of the advantages of modeling is its ability to explore scenarios that are difficult or impossible to observe directly in the field. For example, models can be used to predict long-term system evolution, assess the effectiveness of different grouting strategies, or evaluate potential risks under extreme conditions. However, the reliability of model predictions depends heavily on the quality of input data and the accuracy of underlying assumptions. Parameter uncertainty remains a significant limitation. The processes involved, such as reaction rates and fracture behavior, are difficult to quantify precisely. Calibration and validation of models require extensive field and laboratory data, which may not always be available. Additionally, the computational complexity of fully coupled models can be substantial, limiting their practical application in some cases [46].

Despite these challenges, modeling remains an indispensable tool for both research and practical applications. Ongoing developments in computational methods, data integration, and machine learning offer promising avenues for improving model performance and usability. By combining modeling with field observations and experimental studies, a more comprehensive understanding of the coupled processes governing aquifer response to grouting can be achieved [48]. The key coupled processes and their hydrogeological and geochemical implications are synthesized in **Table 4**.

Table 4. Summary of coupled hydrogeological–geochemical processes, feedback mechanisms, and long-term implications in grouted aquifer systems.

Coupled Process	Hydrogeological Effect	Geochemical Effect	Feedback Mechanism	Long-Term Implication
Mineral precipitation in fractures	Reduced permeability	Removal of ions from solution	Enhances sealing	Improved barrier stability
Mineral dissolution	Increased porosity/permeability	Release of ions	Weakens structure	Potential leakage pathways
Flow reduction	Increased residence time	Enhanced reactions	Accelerates geochemical change	Long-term chemistry shift
Pressure redistribution	Flow diversion	Change reaction zones	Alters transport pathways	Localized risk zones
Grout degradation	Loss of sealing efficiency	Release of materials	Weakening of the barrier	Reduced long-term performance

6. Conclusions

Floor grouting renovation has become an indispensable technique for mitigating water inrush hazards and improving the safety of coal mining operations. This review has demonstrated that, beyond its engineering function, grouting exerts profound and multifaceted influences on aquifer systems, encompassing hydrogeological, geochemical, and coupled processes that evolve over time. A comprehensive understanding of these impacts is essential for balancing mining efficiency with groundwater protection and environmental sustainability. From a hydrogeological perspective, floor grouting significantly modifies aquifer properties by reducing permeability, altering porosity, and disrupting hydraulic connectivity. These changes can effectively isolate high-pressure aquifers and reduce water inflow into mining regions. However, the review highlights that such effects are inherently heterogeneous and may lead to unintended consequences, including flow redistribution, pressure buildup in adjacent zones, and the persistence of preferential pathways. The dynamic evolution of fracture networks and stress conditions further complicates the long-term stability of grouting outcomes.

In terms of geochemical characteristics, the introduction of grout materials initiates complex water–rock–grout interactions that reshape groundwater chemistry. Changes in pH, major ion composition, and redox conditions can influence mineral stability and the mobility of trace elements. While some processes, such as mineral precipitation, may enhance sealing performance and immobilize contaminants, others may pose risks to groundwater quality. The variability of these responses across different geological settings underscores the importance of site-specific evaluation.

A key insight of this review is the strong coupling between hydrogeological and geochemical processes. Physical alterations induced by grouting influence fluid flow and solute transport, while chemical reactions feedback on the aquifer's structure and hydraulic behavior. This bidirectional interaction leads to nonlinear system evolution, making prediction and control challenging, particularly over long-time scales. Current research often treats these processes separately, resulting in a fragmented understanding and limited predictive capability.

The long-term evolution of aquifer systems following grouting remains a critical area of uncertainty. Initial improvements in permeability reduction and pressure control may diminish due to mechanical relaxation, chemical alteration, or mining-induced disturbances. Similarly, geochemical conditions may continue to evolve, with potential delayed impacts on groundwater quality. These findings emphasize the necessity of long-term monitoring and the development of models capable of capturing coupled processes over extended periods. From an environmental perspective, the implications of floor grouting extend beyond the immediate mining area. Changes in groundwater flow and chemistry may affect regional water resources and groundwater-dependent ecosystems. Although these impacts are often localized, they can be significant in sensitive or water-scarce regions. Therefore, integrating environmental considerations into grouting design and implementation is essential.

To address these challenges, future research should focus on several key directions. First, there is a need for more integrated studies that combine hydrogeological, geochemical, and mechanical analyses, supported by field data and laboratory experiments. Second, the development of environmentally friendly grouting materials with improved long-term stability should be prioritized. Third, advances in monitoring technologies and data integration are required to better characterize subsurface processes and reduce uncertainty. Finally, the application of coupled numerical models should be expanded to support decision-making and optimize grouting strategies. In summary, floor grouting renovation is both a powerful engineering tool and a significant driver of subsurface change. Its successful and sustainable application depends on a holistic understanding of the complex processes it induces. By advancing interdisciplinary research and adopting integrated management approaches, it is possible to enhance the effectiveness of grouting while minimizing its environmental impacts, thereby supporting the safe and sustainable development of coal resources.

Funding

This work was supported by the Fundamental Research Funds for the Central Universities 3142024016.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All the data is presented in the article.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

References

[1] Hasii, O., Gasii, G., 2024. Coal mining and water resources: Impacts, challenges, and strategies for sustainable environmental management. IOP Conference Series: Earth and Environmental Science. 1348, 012017.

[2] Wang, D., Sui, W., Ranville, J.F., 2022. Hazard identification and risk assessment of groundwater inrush from a coal mine: A review. Bulletin of Engineering Geology and the Environment. 81(10), 421.

[3] Zhai, M., Bai, H., 2023. Precise application of grouting technology in underground coal mining: Water inrush risk of floor elimination. Environmental Science and Pollution Research. 30(9), 24361–24376.

[4] Zhai, M., Bai, H., Wu, L., et al., 2022. A reinforcement method of floor grouting in high-water pressure working face of coal mines: A case study in Luxi coal mine, North China. Environmental Earth Sciences. 81(1), 28.

[5] Nonveiller, E., 2013. Grouting Theory and Practice, Vol. 57. Elsevier: Amsterdam, The Netherlands.

[6] Christodoulou, D., Lokkas, P., Markou, I., et al., 2021. Principles and developments in soil grouting: A historical review. WSEAS Transactions on Advances in Engineering Education. 18, 175–191.

[7] Quan, H., Yang, X., Yu, H.-J., et al., 2025. Classification and research status of solid waste grouting materials: A review. Waste Management & Research. 43(11), 1694–1715.

[8] Qiao, W., Li, W., Zhang, S., et al., 2019. Effects of coal mining on the evolution of groundwater hydrogeochemistry. Hydrogeology Journal. 27(6), 2245–2262.

[9] Raghavendra, N.S., Deka, P.C., 2015. Sustainable development and management of groundwater resources in mining affected areas: A review. Procedia Earth and Planetary Science. 11, 598–604.

[10] Huang, W., Sui, J., Wang, Y., et al., 2023. Study of the mining and aquifer interactions in complex geological conditions and its management. Scientific Reports. 13(1), 9462.

[11] Li, X., Xiong, X., Chen, G., et al., 2025. Dynamic response modeling of mine water flooding following grouting and rehabilitating of coalbed water-conducting channels. Geoenvironmental Disasters. 12(1), 24.

[12] van der Lee, J., De Windt, L., 2001. Present state and future directions of modeling of geochemistry in hydrogeological systems. Journal of Contaminant Hydrology. 47(2–4), 265–282.

[13] Zhang, Y., Li, L., Mu, W., et al., 2026. Experimental and numerical study on cross-layer mechanical characteristics and failure mechanism induced by grouting in interbedded rocks. Journal of Mechanics. 42, 12–39.

[14] Liu, Z., Dong, S., Zheng, S., et al., 2025. Research on advanced grouting curtain technology for water interception and control at the source of aquifer in coal seam roof. Scientific Reports. 15(1), 20354.

[15] Liu, X., Sun, J., Liu, B., et al., 2025. Grouting Flow in Deep Fractured Rock: A State-of-the-Art Review of Theory and Practice. Fluid Dynamics & Materials Processing. 21(8), 2047–2073.

[16] Sang, H., Liu, B., Liu, Q., et al., 2024. Study of grouting reinforcement mechanism in fractured rock mass and its engineering application. International Journal of Geomechanics. 24(5), 04024057.

[17] Naskar, J., Jha, A.K., Singh, T., 2024. A comprehensive review of grouts: Unraveling biogrout technologies for environmental sustainability and limitations. Journal of Hazardous, Toxic, and Radioactive Waste. 28(3), 03124001.

[18] Ogienagbon, A.A., Khalifeh, M., 2025. Development of Geopolymer as Treatment Fluid for Remedial Operations—Characterization and Comparison with State-of-the-Art Materials. SPE Journal. 30(9), 5501–5515.

[19] Zheng, H., Qian, Z., Gao, G., et al., 2025. Research on the law and mechanism of potential pollution of groundwater quality by grouting with cement-based materials. Environmental Science and Pollution Research. 32(27), 16489–16501.

[20] Qian, Z., Zheng, H., Jiang, C., et al., 2026. Experimental study on patterns and mechanisms of water quality degradation in water-rich sand formations induced by different types of chemical grouts. Journal of Contaminant Hydrology. 281, 104947.

[21] Warner, J., 2004. Practical Handbook of Grouting: Soil, Rock, and Structures. John Wiley & Sons: Hoboken, NJ, USA.

[22] Rafi, J., Stille, H., 2021. A method for determining grouting pressure and stop criteria to control grout spread distance and fracture dilation. Tunnelling and Underground Space Technology. 112, 103885.

[23] Yihdego, Y., 2017. Hydraulic in situ testing for mining and engineering design: Packer test procedure, preparation, analysis and interpretation. Geotechnical and Geological Engineering. 35(1), 29–44.

[24] Liu, Q., Sun, L., 2019. Simulation of coupled hydro-mechanical interactions during grouting process in fractured media based on the combined finite-discrete element method. Tunnelling and Underground Space Technology. 84, 472–486.

[25] Li, B., Zhang, J., Liu, Y., et al., 2022. Interfacial porosity model and modification mechanism of broken coal grouting: A theoretical and experimental study. Surfaces and Interfaces. 33, 102286.

[26] Duan, J., Mu, W., Li, L., et al., 2024. Slurry flow mechanism with time-varying viscosity in regional long-hole grouting for floor reinforcement. Physics of Fluids. 36(8), 083115.

[27] Zhang, Y.-Q., Wang, J.-H., Chen, J.-J., et al., 2017. Numerical study on the responses of groundwater and strata to pumping and recharge in a deep confined aquifer. Journal of Hydrology. 548, 342–352.

[28] Yang, Y., Kang, Z., Qiu, S., et al., 2025. Study on Influence of Grouting on Mechanical Characteristics and Stress Concentration in Hole-Containing Rock. Applied Sciences. 15(10), 5245.

[29] Hou, Z., Huang, L., Zhang, S., et al., 2024. Identification of groundwater hydrogeochemistry and the hydraulic connections of aquifers in a complex coal mine. Journal of Hydrology. 628, 130496.

[30] He, S., Qian, Z., Zheng, H., et al., 2025. Study on grout seepage diffusion and fracture deformation laws in fractured rock mass based on visualized experiments. Environmental Earth Sciences. DOI: https://dx.doi.org/10.2139/ssrn.5046833

[31] Qu, S., Wang, G., Shi, Z., et al., 2022. Impact of mining activities on groundwater level, hydrochemistry, and aquifer parameters in a Coalfield's overburden aquifer. Mine Water and the Environment. 41(3), 640–653.

[32] Ali, N., Chappuies, J., Sloan, G., et al., 2025. A global perspective on electrical resistivity tomography, electromagnetic and ground penetration radar methods for estimating groundwater recharge zones. Frontiers in Water. 7, 1636613.

[33] Zhang, Y., Sun, Y., Yan, Y., et al., 2026. Research Status, Challenges and Future Perspectives of Geological Hazard Monitoring Methods in Mining Areas. Remote Sensing. 18(9), 1333.

[34] Bath, A., 2006. Geochemical Investigations of Groundwater Stability. SKI (Swedish Nuclear Power Inspectorate): Stockholm, Sweden.

[35] Wali, S., Usman, A.A., Usman, A.B., et al., 2024. Impact of geology on hydrogeological and hydrochemical characteristics of groundwater in tropical environments: A narrative review. International Journal of Hydrology. 8(6), 202–221.

[36] Jorne, F., Henriques, F.M., 2016. Evaluation of the grout injectability and types of resistance to grout flow. Construction and Building Materials. 122, 171–183.

[37] Grangeon, S., Debure, M., Montouillout, V., et al., 2024. Mineralogical and geochemical composition of a cementitious grout and its evolution during interaction with water. npj Materials Degradation. 8(1), 75.

[38] Kudryashova, O.S., Elokhov, A.M., Khayrulina, E.A., et al., 2021. Composition for rock grouting based on insoluble calcium salts for groundwater protection. Environmental Earth Sciences. 80(5), 205.

[39] Grivé, M., Duro, L., Domènech, C., et al., 2011. Redox evolution of a cementitious geological disposal facility. In Proceedings of the 13th International High-Level Radioactive Waste Management Conference (IHLRWMC), Albuquerque, NM, USA. 10–14 April 2011.

[40] Frohne, T., Rinklebe, J., Diaz-Bone, R.A., et al., 2011. Controlled variation of redox conditions in a floodplain soil: Impact on metal mobilization and biomethylation of arsenic and antimony. Geoderma. 160(3–4), 414–424.

[41] Cao, B., Xu, J., Wang, F., et al., 2021. Vertical barriers for land contamination containment: A review. International Journal of Environmental Research and Public Health. 18(23), 12643.

[42] Kyser, T.K., Leybourne, M.I., Layton-Matthews, D., 2020. Advances in the use of isotopes in geochemi-

cal exploration: Instrumentation and applications in understanding geochemical processes. Geochemistry: Exploration, Environment, Analysis. 20(2), 199–204.

[43] Nowak, M.E., Schwab, V.F., Lazar, C.S., et al., 2017. Carbon isotopes of dissolved inorganic carbon reflect utilization of different carbon sources by microbial communities in two limestone aquifer assemblages. Hydrology and Earth System Sciences. 21(9), 4283–4300.

[44] Glynn, P.D., Plummer, L.N., 2005. Geochemistry and the understanding of ground-water systems. Hydrogeology Journal. 13(1), 263–287.

[45] Zhan, H., Liu, Q., Wu, Q., et al., 2024. Effects of deep coal mining on groundwater hydrodynamic and hydrochemical processes in a multi-aquifer system: Insights from a long-term study of mining areas in ecologically fragile western China. Journal of Contaminant Hydrology. 265, 104386.

[46] Inazumi, S., Shakya, S., 2024. A comprehensive review of sustainable assessment and innovation in jet grouting technologies. Sustainability. 16(10), 4113.

[47] Luna, M., Arcos, D., Duro, L., 2006. R-06-107: Effects of Grouting, Shotcreting and Concrete Leachates on Backfill Geochemistry. Svensk Kärnbränslehantering AB Swedish Nuclear Fuel And Waste Management Co.: Stockholm, Sweden.

[48] Ma, G., Wang, Z., Wang, H., 2025. Grouting geological model (GGM): Definition, characterization, modeling, and application in determining grouting material and pressure. Rock Mechanics and Rock Engineering. 58(6), 6513–6538.