sustainability

MDPI

Review

Environmental Impacts of Shale Gas Development on Groundwater, and Flowback and Produced Water Treatment Management: A Review

Shubiao Pan [1,2,3], Ye Zhang [1,2,*], Peili Lu [3,4,*], Demin Yang [1,2,3], Yongkui Huang [1,2], Xiaochuan Wu [1,2], Pei He [1,2] and Dongxin Guo [5]

1 National and Local Joint Engineering Research Center of Shale Gas Exploration and Development, Chongqing Institute of Geology and Mineral Resources, Chongqing 401120, China; pan_shubiao@163.com (S.P.)
2 Key Laboratory of Shale Gas Exploration, Ministry of Natural Resources, Chongqing Institute of Geology and Mineral Resources, Chongqing 401120, China
3 Department of Environmental Science, College of Environment and Ecology, Chongqing University, Chongqing 400045, China
4 State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing 400044, China
5 Chongqing Huadi Resources and Environment Technology Co., Ltd., Chongqing 401120, China
* Correspondence: zhangye_sg@vip.163.com (Y.Z.); lupl@cqu.edu.cn (P.L.)

Abstract: The rapid expansion of shale gas development has revolutionized global energy markets, yet it has also introduced substantial environmental challenges, particularly concerning groundwater resources. This comprehensive review systematically examines the multifaceted impacts of shale gas extraction on groundwater, with a focus on contamination mechanisms, pollutant sources, and mitigation strategies. The study identifies key operational stages—exploration, drilling, hydraulic fracturing, and flowback—as potential sources of groundwater contamination. Inorganic pollutants, including heavy metals and radionuclides, as well as organic compounds such as hydrocarbons and chemical additives, are identified as primary contaminants. The review critically evaluates current wastewater treatment technologies, including reinjection, internal reuse, and advanced desalination methods, highlighting their efficacy and limitations. Additionally, the study proposes a refined environmental management framework that integrates wellbore integrity optimization, enhanced shale gas wastewater treatment, and stringent monitoring protocols. The adoption of clean fracturing technologies and renewable energy applications is recommended to minimize environmental footprints. By establishing comprehensive baseline data and robust pollution monitoring systems, this research provides a scientific foundation for sustainable shale gas development, ensuring the protection of groundwater resources. This review emphasizes the imperative of balancing energy security with environmental sustainability, offering actionable insights for policymakers, industry stakeholders, and environmental scientists.

Keywords: flowback and produced water; groundwater contamination; hydraulic fracturing; contamination mechanisms; pollutant sources; treatment technologies

check for updates

Academic Editor: Andrea G. Capodaglio

Received: 5 May 2025
Revised: 28 May 2025
Accepted: 3 June 2025
Published: 5 June 2025

Citation: Pan, S.; Zhang, Y.; Lu, P.; Yang, D.; Huang, Y.; Wu, X.; He, P.; Guo, D. Environmental Impacts of Shale Gas Development on Groundwater, and Flowback and Produced Water Treatment Management: A Review. *Sustainability* **2025**, *17*, 5209. https://doi.org/10.3390/su17115209

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

By leveraging advanced technologies such as hydraulic fracturing (HF) and horizontal drilling, the rapid development of shale gas as a prominent unconventional energy resource has profoundly reshaped the global energy landscape [1,2]. In numerous countries,

especially the USA, China, Canada, the UK, Australia, and Turkey, shale gas extraction has emerged as a cornerstone of energy security and economic growth, and also been demonstrated to contribute to the reduction in greenhouse gas emissions as alternatives to traditional coal-based fuels [3]. Notably, China possesses the world's largest technically recoverable shale gas reserves, accounting for 15% of the global total [4]. To date, four national shale gas demonstration zones have been established in China, namely Fuling, Changning-Weiyuan, Zhaotong, and Yanchang [5]. These zones have been strategically developed to facilitate the exploration and production of shale gas resources, thereby supporting the transition towards cleaner energy sources. HF is a widely utilized well stimulation technique in the oil and gas industry. This method involves injecting fracturing fluids, a mixture of water, sand, and specific chemical additives, under high pressure to create fractures in rock formations, thereby enhancing their permeability. This technology has enabled the extraction of substantial quantities of oil and natural gas from shale formations, which were previously inaccessible.

However, the rapid expansion of the shale gas industry has raised significant environmental concerns. These include induced seismicity [6], greenhouse gas emissions [1,7], and water-related issues such as the contamination of shallow groundwater and surface water, as well as the depletion of water resources [8,9]. Groundwater, a vital source of freshwater for drinking, agricultural, and industrial purposes, is particularly susceptible to contamination during various stages of shale gas development, including exploration, drilling, fracturing, flowback and production. The potential threats to agricultural irrigation and residential drinking water safety have become a major public concern [1,10–12]. Additionally, the substantial water demand for shale gas extraction is noteworthy. For instance, in the United States, the average wastewater production per well during the first 5–10 years ranges from 1.7 to 14.30 $\times$ 10^3 m^3 [13], while in the Sichuan Basin, the average water consumption for fracturing per well is approximately 3.4 $\times$ 10^4 m^3 [14].

Throughout the lifecycle of shale gas development, large volumes of wastewater, characterized by high salinity and complex chemical compositions, are generated by HF operations. These byproducts pose significant risks to the geological environment, particularly shallow groundwater [15,16]. Groundwater contamination may be potentially caused by the complex interplay of chemical, physical, and geological processes inherent in shale gas extraction. HF involves the use of numerous chemical substances. The United States Environmental Protection Agency (EPA) has identified 1173 distinct chemical compounds used in the preparation of HF fluids, including acids, aromatic hydrocarbons, bases, hydrocarbon mixtures, polysaccharides, and surfactants [17]. Hill et al. (2022) [18] identified 1244 unique HF chemicals through research on HF chemistry trends from 2014 to 2020, comparing them with a list of reference chemicals that encounter drinking water, food, or cosmetics (not related to HF).

Heavy metals, radionuclides, hydrocarbons, and chemical additives used in HF could migrate into aquifers through wellbores, fractures, or surface spills, thereby posing significant risks to human health and ecosystems. Potential contamination pathways may include the leakage of drilling fluids, the improper storage of drill cuttings, the migration of deep-seated fluids through induced fractures to shallow aquifers, and the spills or improper disposal of flowback and produced water (Figure 1) [15,19]. Despite extensive research on this topic, a comprehensive understanding of the contamination mechanisms, the types and sources of pollutants, and the effectiveness of mitigation strategies remains incomplete.

This study aims to address these critical gaps by providing a systematic review of the impacts of shale gas development on groundwater. Specifically, the research focuses on three key areas: (1) identifying the stages of shale gas operations that pose the greatest risks to groundwater, (2) characterizing the types and sources of pollutants associated

with these operations, and (3) evaluating current wastewater treatment technologies and their efficacy in mitigating contamination. Furthermore, the study proposes a refined environmental management framework designed to minimize contamination risks and promote sustainable shale gas development. This research is significant for informing policymakers, industry stakeholders, and environmental scientists about best practices to mitigate shale gas extraction's environmental impacts. It highlights the need for a holistic approach to shale gas development, emphasizing environmental sustainability and the long-term protection of groundwater systems. By providing a comprehensive analysis, the study aims to advance sustainable energy development and environmental conservation efforts.

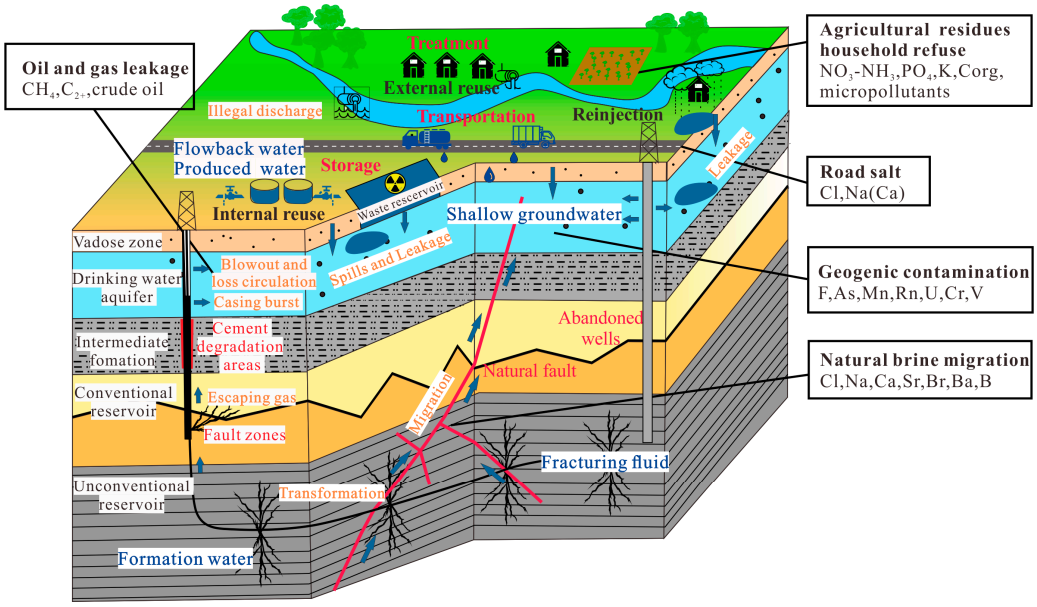


Figure 1. Conceptual model of groundwater contamination mechanism and hazard pattern caused by shale gas development (modified from Bondu et al., 2021 [19] and He et al., 2022 [15]).

2. Effects of the Whole Progress of Shale Gas Development on Groundwater Water

2.1. Exploration and Preparation

Seismic exploration activities during the shale gas exploration phase may impact the groundwater table, potentially altering flow paths and dynamic equilibrium [20]. These activities could also cause temporary chemical changes, including alterations in groundwater hydrochemistry, turbidity, and isotopic elemental concentrations [21].

Conversely, shale gas extraction is a complex industrial process that requires significant preparatory work before drilling begins. This includes comprehensive site investigations, site leveling, infrastructure construction, and the transportation of equipment and raw materials. Among these activities, road construction and transportation are significant sources of environmental contamination, posing a persistent threat to groundwater [22,23]. The construction and maintenance of roads are particularly problematic, especially in the context of rainfall and road surface runoff, which can contaminate surrounding surface and groundwater resources. The main pollutants include total suspended solids (TSS), specific organic pollutants (such as aliphatic and aromatic hydrocarbons and polycyclic aromatic hydrocarbons or PAHs), heavy metals, and chlorides [22,24]. These pollutants are carried by runoff from the road surface, deposited on adjacent vegetation and soil, and then infiltrate into the ground, entering the aquifer [25].

In the context of shale gas extraction, it is also crucial to consider the preparation of working fluids, such as drilling and fracturing fluids, and mechanical lubricants. The transportation and storage of these raw materials carry the risk of spills or leaks of toxic substances, including chemical additives, which can contaminate groundwater resources as extraction activities progress.

2.2. Drilling

The development of shale gas resources involves horizontal drilling and hydraulic fracturing, which require the use of drilling fluids. These fluids, which can include water-based, oil-based, synthetic-based, and gas-based formulations [26], contain various chemical additives such as lubricants, corrosion inhibitors, and pH regulators [27]. While drilling fluids play a critical role in stabilizing wellbores and removing drill cuttings [28], their improper handling or leakage can pose risks to groundwater quality [29].

The potential contamination of groundwater during shale gas drilling is primarily attributed to fluid migration through compromised well integrity, surface spills, and natural pathways (Figure 1). Historical records indicate significant variability in leakage rates across regions, with reported well integrity failures ranging from 2% to 50% in older wells [30], while modern wells exhibit lower rates (0.004–0.06%) due to improved construction practices and stringent regulations [31]. Documented incidents often involve methane migration, with cases such as interwell communication during hydraulic fracturing reported in Alberta, Canada, where 39 instances were identified among 5349 horizontal wells [32].

The primary factors contributing to leakage include mechanical failures in casing and cement, corrosion of well materials, and inadequate zonal isolation (Figure 1) [33–36]. Horizontal drilling exacerbates these risks, as achieving uniform cementation in deviated boreholes remains challenging, potentially creating pathways for fluid migration. Aging infrastructure further elevates leakage susceptibility, with older wells showing higher failure rates due to material degradation [30]. Fault reactivation and fracture propagation may be triggered by drilling and fracturing pressure, with the potential for fractures to extend into adjacent wells or formations, especially in regions with dense well networks [37]. Simulations of water flushing through sandstone demonstrate that in high-velocity dynamic water environments, clay mineral softening, water–rock interactions, and swelling reactions can weaken rock particle cementation [38–40]. This promotes the development of microfractures and pores.

Leakage magnitude is influenced by geological conditions, well design, and operational practices. Overpressured reservoirs, permeable faults, and shallow fracturing depths enhance vertical fluid migration risks [41,42]. Simulations suggest that methane migration through degraded cement can occur over months to decades, depending on cement permeability and reservoir pressure [37]. Furthermore, inadequate baseline groundwater monitoring and variable methane concentrations in aquifers complicate impact assessments.

Mitigation strategies emphasize enhanced well construction, including multi-barrier casing systems and advanced cement evaluation tools, alongside regulatory mandates for groundwater monitoring. To mitigate these risks, best practices such as proper fluid recycling, robust well integrity testing, and the installation of multiple isolation barriers are essential. Despite technological advancements, the cumulative long-term risks of subsurface fluid migration necessitate ongoing research to refine predictive models and monitoring protocols [31]. Furthermore, advancements in monitoring protocols and baseline groundwater characterization are critical for detecting and addressing potential contamination events.

2.3. Hydraulic Fracking

Shale gas reservoirs are distinct from conventional natural gas reservoirs due to their ultra-low porosity and permeability. A significant portion of shale gas is adsorbed onto the inner surfaces of the reservoir's pores and fractures, while free gas occupies the pore spaces within larger pores and fractures that are not filled with adsorbed gas and water. To enhance the production capacity of shale gas wells, HF is used to create a network of fractures around the horizontal wellbore, which improves fluid mobility and increases single-well production and recovery rates shale gas.

HF is a key technology for increasing shale gas production. High-viscosity fluids are injected into the well at a rate that exceeds the stratum's absorption capacity, generating pressures that exceed local geological stress and the rock's tensile strength. This leads to the formation of fractures in the strata. As the proppant-carrying fracturing fluid is injected, the fractures extend, enhancing production. In HF, the fracturing fluid acts as a conduit for energy, facilitating fracture formation and extension and the transportation of proppant [43]. The fluid's composition varies based on geological conditions and typically includes water, proppant, and various chemical additives. Although chemical additives make up a small portion of the fracturing fluid (Table 1), they can be a significant source of groundwater contamination [44]. These additives include acids, friction reducers, surfactants, potassium chloride, biocides, corrosion inhibitors, gelling agents, iron control agents, pH adjusters, and cross-linking agents [45–47].

Table 1. Purposes and proportion of each component of fracturing fluid in hydraulic fracturing operation.

Additive	Purpose	Fraction %
Gel Agent	Increases the viscosity of the fracturing fluid, enhances sand suspension, aids in proppant transport	0.05
Crosslinking Agent	Chemically binds individual gel polymer molecules to maintain fluid viscosity, facilitating proppant transport	0.007
Lubricant	Reduces the interfacial tension between the fluid and pipe surface, maintaining laminar flow during pumping	0.07
Breaker	Reverses crosslinking, reduces viscosity, improves gas production efficiency, aids in fracturing fluid recovery	0.06
pH Control Agent	Enhances the effectiveness of crosslinking agents	0.01
Acid	Cleans and dissolves minerals, facilitating rock fracturing	0.15
Corrosion Inhibitor	Prevents corrosion of casings due to acids and salts	0.002
Scale Inhibitor	Prevents the formation of scale (mineral deposits) within pipelines	0.09
Iron Control Agent	Prevents iron ion precipitation	0.006
Clay Stabilizer	Prevents clay swelling in shale formations	0.120
Biocide	Sterilizes and inhibits bacteria in the fracturing fluid	0.060
Surfactant	Controls the optimal viscosity of the fracturing fluid, reduces interfacial tension between the fracturing fluid and shale	0.075

The scientific community is divided on whether fluids associated with shale reservoirs, such as highly mineralized formation water, fracking fluids, and fugitive methane, can ascend through natural preferential pathways to shallow aquifers, contaminating groundwater [31]. The general consensus is that fluids are unlikely to travel long distances through geological layers above shale reservoirs without clear migration pathways. Zoback and Arent 2014 [48] highlighted that HF, typically performed at considerable depths, results in fractures confined to a maximum extension of about 600 m. They also suggested that the depressurization of shale formations due to gas extraction effectively curbs upward

fluid migration. This perspective is supported by Davies et al. (2012) [49], who found that hydraulic fractures typically extend no more than 350 m. Lange et al. (2013) [50] and Kissinger et al. (2013) [51] advocated for a minimum HF depth exceeding 1 km to mitigate groundwater contamination risks.

Reagan et al. (2015) [52] used multiphase simulation studies to show that under equilibrium pressure and natural gas extraction conditions, fluid migration occurs from the aquifer toward the reservoir, precluding significant impact on shallow groundwater quality. Missimer and Maliva (2020) [53] concluded that the potential for groundwater contamination from HF or oil production in southern Florida is exceedingly low. Birdsell et al. (2015) [42] reviewed fluid migration research and concluded that the likelihood of fluids migrating to shallow groundwater is minimal, especially considering capillary imbibition within the shale and suction from gas production wells. Liu et al. (2024) [54] applied a migration risk assessment model and determined that the ingress of pollutants is minimal, with an average estimated time of 1545 days for pollutants to reach the aquifer.

However, Nowamooz et al. (2015) [37] suggested that overpressure in shale gas reservoirs could lead to the migration of methane and mineralized fluids toward the surface or shallow freshwater aquifers. Their simulations, which account for wellbore cement degradation and casing integrity loss, suggested that methane could penetrate the 800 m overlaying formation in a timeframe ranging from months to 30 years. They also observed that the potential presence of upwardly migrating methane and associated fluids was unlikely to substantially affect shallow groundwater quality. Dusseault and Jackson (2014) [55] documented incidents of HF affecting adjacent wells, with geomechanical processes related to cement shrinkage causing gas migration from deep within the surface casing to the exterior. Gassiat et al. (2013) [56] supported the possibility of long-term fluid migration along permeable faults under conditions of sustained high pressure within shale gas reservoirs. However, many experts deem the maintenance of overpressure post-shale gas production highly improbable, questioning the likelihood of such upward fluid migration [41,55,57,58]. Hammond et al. (2024) [59] conducted a comprehensive analysis of natural gas seepage incidents within the Marcellus Shale and identified hydrogeological conditions as the main factors influencing the occurrence of natural gas pollution. They proposed a predominant migration pathway that initiates with an upward movement from the gas-bearing strata, traversing through the well's annular space and into the confined aquifer. The gas is hypothesized to disperse laterally toward potential discharge points or escape through vertically oriented fractures, ultimately reaching streams, water wells, or being released into the atmosphere. The relationship between HF and shallow groundwater is complex, with the potential for contamination being a key concern, though studies suggest that the risk is generally low due to geological constraints and the depth of operations.

2.4. Flowback and Gas Production

Following HF, the subsequent phase in shale gas development is flowback, where fluids from the shale formation are brought to the surface through the gas well, creating flowback water. These fluids are a complex mixture of fracturing fluid and formation water that have undergone geochemical reactions, resulting in a chemically diverse composition. The flowback period typically lasts from several weeks to two months [46,60]. After this period, it is crucial to treat the moisture and impurities in the extracted shale gas. The water that emerges post-production stage, after being subjected to gas–liquid separation processes, is termed produced water. Given that the distinction between flowback water and produced water is often subjective, this paper collectively refers to them as flowback

and produced water (FPW) without drawing a clear line between the two, which also represents a narrow definition of shale gas wastewater.

FPW is the primary contaminant source that can affect shallow groundwater during the flowback and production phases of shale gas extraction. Initially, flowback water consist mainly of fracturing fluid with a smaller portion of formation water [9,61]. Over time, the proportion of fracturing fluid decreases while that of formation water increases, eventually reaching equilibrium. In North America, the proportion of original formation water in flowback water increased from 5% on the first day to 50% after 12 days [62]. In China's Weiyuan shale gas field, formation water made up 80% of the produced water after one year [63]. This suggests that formation water is more likely to impact shallow groundwater quality over the lifetime of a shale gas well compared to FPW [9,63]. It is important to note that shallow groundwater contamination may also result from the migration of salinized formation water from adjacent strata to shallow groundwater layers (Figure 1). Some studies suggest that the salinization of shallow groundwater may be a natural process, where formation water migrates along structural deformation zones and through faults and fractures, often observed in shallow aquifers in valley bottoms or faulted areas [8,64,65]. Dong et al. (2024) [66] conducted a comprehensive survey of shallow groundwater at various shale gas exploitation sites in the Sichuan Basin, and found no correlation between shallow groundwater quality and the minimum distance to shale gas well pads. Salinized groundwater samples were collected near fault zones, with the primary source of salinization being Triassic stratigraphic brines.

FPW contains a variety of hazardous substances, including heavy metals, halogens, organic pollutants, and radioactive elements, often in concentrations exceeding safety limits. If these substances enter surface or groundwater, they can contaminate these resources, posing risks to human health. The main routes of environmental contamination by FPW are leakage and improper disposal (Figure 1). Spills typically occur during the storage, transport, or disposal of return fluids, due to design flaws, extreme weather, or operational errors [67,68]. The EPA documented 225 instances of FPW leakage between 2006 and 2012 in the United States, a number that may underestimate the actual occurrences [17]. The road transport of FPW presents a substantial groundwater contamination risk, driven by three key factors: (1) massive volumes (25.9 billion barrels in 2021, with Texas alone accounting for 8.1 billion barrels [69]); (2) hazardous constituents including high salinity, heavy metals (Ba, Sr), naturally occurring radioactive materials (NORMs), and residual fracking chemicals; and (3) environmentally sensitive transport routes through agricultural lands, wetlands, and residential areas. Poor road conditions, particularly unpaved rural routes, increase spill risks due to vehicle instability and heavy traffic. Arid regions face additional risks as road dust facilitates pollutant infiltration. Although 95.7% of FPW is ultimately injected underground, transportation remains a critical contamination pathway due to insufficient spill monitoring and reporting requirements in many states.

The improper disposal of FPW can also contaminate groundwater. While deep well injection and reuse can mitigate environmental impact, FPW must still be treated before discharge. However, due to the complex composition of FPW, conventional treatment technologies may not fully remove harmful substances, risking contamination of surface water and soil upon direct discharge. Even after treatment, Marcellus FPW still shows elevated chloride and bromide concentrations, significantly increasing these elements downstream [70]. There has also been a substantial increase in radium content in river sediment. Ni et al. (2022) [71] found that the discharge of treated shale gas wastewater could salinize rivers, increasing chloride concentrations approximately 10-fold downstream of the discharge point.

Furthermore, shale gas production, which can result in methane gas migration, may also lead to shallow groundwater contamination. During shale gas production, gas escapes from the formation can lead to the diffusion of gases like methane into the aquifer through conducive transport pathways [8,31,65,72]. Investigations of private drinking water wells near shale gas drilling and HF sites have revealed significant increases in methane concentrations, exceeding established contamination thresholds [72,73]. Although methane is not directly toxic, its presence can introduce potential hazards, especially when it accumulates in drinking water or forms gas plumes, leading to hypoxic conditions that affect water quality or facilitate the migration of harmful pollutants [74,75].

2.5. Freshwater Resource Consumption

HF is essential for shale gas development, but it requires significant freshwater resources, which could affect water availability and pose a constraint on sustainable shale gas development, particularly in water-scarce regions [76–80]. Most of the water used for HF comes from surface or shallow groundwater sources, with only about 5% being reused from FPW [81,82]. Groundwater environmental quality is significantly impacted by exploitation activities, with hydrological dynamics being altered, contaminant migration being accelerated, and geochemical balances in aquifer systems being disrupted. The volume and quality of water retrieved after fracturing, known as FPW, are crucial for the feasibility of wastewater recycling and safe management without causing environmental harm [13,46]. In the United States, a single well's HF consumes between 12,000 and 30,000 m^3 of water, while in Canada, it is typically below 15,000 m^3. In contrast, China's shale gas development consumes more, with figures ranging from 25,000 to 35,000 m^3. Data from the Weiyuan gas field in the Sichuan Basin show that HF per well requires 34,000 m^3 of water, with a flowback volume of 19,800 m^3 during the first year of production [14]. These variations reflect the deep burial depth and complex geological conditions of shale gas reservoirs.

Despite the high water demand for HF, its impact on overall production and domestic water demand is relatively minor, with the United States' average annual water consumption being approximately 167 million m^3, less than 1% of national production and domestic water use [67]. However, in arid regions or areas with a dense distribution of gas wells, HF can significantly impact water resources, as evidenced by declines in groundwater levels and alterations in river flows in certain areas of Texas and Pennsylvania [83]. Chinese scholars predict that annual water consumption will continue to increase with the advancement of shale gas development. They expect water usage for HF to reach 50–65 million m^3, with FPW production reaching 50–55 million m^3 per year. Additionally, they project that the freshwater dilution of FPW will reach 25 million m^3 per year by 2030 [14].

3. Types and Sources of Potential Pollutants

3.1. Inorganic Pollutants

3.1.1. Types of Inorganic Pollutants

As discussed, shallow groundwater can be contaminated with varying degrees of inorganic pollutants throughout the shale gas development process. Inorganic pollutants in fluids related to shale gas development—such as drilling fluids, fracturing fluids, and FPW—can be broadly categorized into major and trace elements (e.g., Cl, Na, Ba, Sr, B, Mn), radionuclides (e.g., Ra-226, Ra-228, U-238), and trace metals and metalloid elements, including As, Cd, Cr, Ni, Pb, Sb, and Se (Figure 2) [12,22,61,71,84]. The quality characteristics of FPW vary greatly among different shale basins (Table 2). Furthermore, even within the same basin, the composition of the wastewater can change throughout the life cycle of a well [63]. The study on inorganic ion characteristics in groundwater from shale gas extraction areas effectively reflects the impacts of extraction activities. Uncontaminated

shallow groundwater typically exhibits low TDS and low Cl^- levels, with a predominant HCO_3-Ca hydrochemical type. However, when contaminated by shale gas flowback fluids, the groundwater shows significant increases in characteristic components such as Ba (up to 714 μg/L), Li (423–450 μg/L), and Cl^- (278–288 mg/L). Diagnostic ratios like Br/Cl and B/Cl distinctly deviate from background values [9]. These inorganic ion signatures serve as effective tracers for groundwater contamination from shale gas operations, with leakage from wastewater storage ponds identified as a primary contamination pathway.

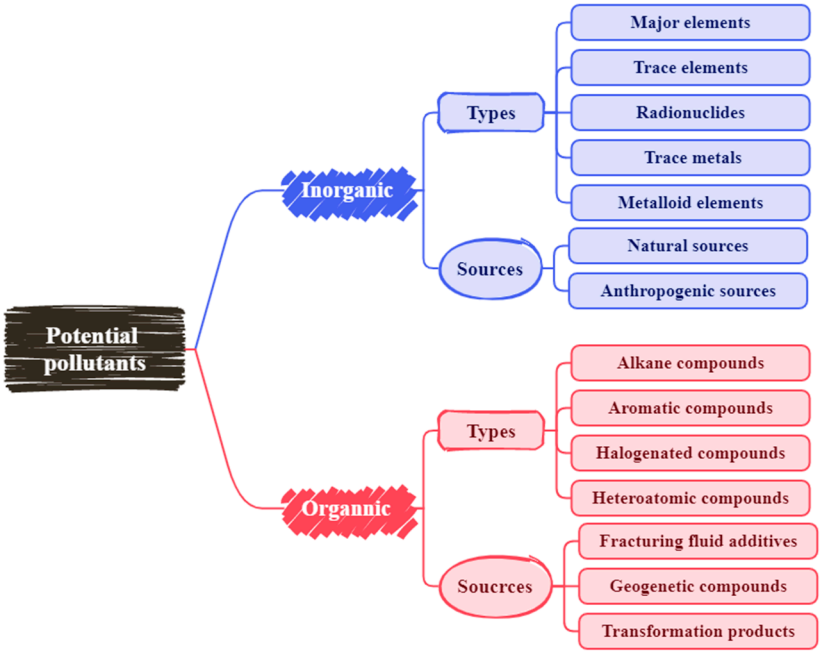


Figure 2. Types and sources of potential pollutants in groundwater for shale gas development.

Table 2. Characteristics of FPW in different regions (unit, mg/L).

Region	pH	TDS	COD	TOC	TSS	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	Br^-	Ref.
Marcellus Basin, USA	5.1~8.42	680~345,000	195~36,600	1.2~1530	4~7600	69.2~117,000	37.8~41,000	17.3~2550	64.2~196,000	0~763	0.2~1990	[60]
Bakken Basin, USA	5.0~5.4	269,380~295,320	1700~2260	91~315	2660~7500	12,271~74,600	372~15,346	118~1299	89~136,220	102~531.6	37.1~601	[85]
Eagle Ford Basin, USA	4.3~8.9	1033~398,024	-	-	160~1559	148~123,775	1~40,992	1~17,203	490~245,367	1~14,100	260	[85]
Denver-Julesburg Basin, USA	7.0~8.2	30,545~30,655	2960~3140	637~653	837~923	-	-	-	-	-	-	[86]
Niobrara/DJ Basin, USA	6.56~7.42	14,220~445,020	628~8125	95~758	80~1297	5233~14,794	57~1204	14~130	6524~27,103	5.4~258	57~259	[85]
Ordos Basin, China	-	8640~9630	1577~2318	700~1514	80~110	-	29.5~508.7	3.8~86.2	2800~24,700	0~38.9	-	[87]
Sichuan Basin (Changning), China	7.1~7.3	30,859~31,204	1228~1259	-	53~93	743.0~1049.1	532.1~756.5	56.4~62.0	541.1~3030.2	57.5~257.3	309~371	[88]
Sichuan Basin (Fuling), China	6.58~7.52	268,000~402,000	-	-	-	12,154~14,654	344~501	32~52	17,620~24,250	-	89~114	[71]
Sichuan Basin (Weiyuan), China	-	-	-	-	-	5856~8887	118~316	26~49	7342~15,253	-	40~81	[63]
Sichuan Basin (Anyue), China	-	-	-	-	-	3113~12,578	119~444	4~85	4645~19,695	1.6~286	15~80	[61]

The concentrations of these geological elements may exceed levels harmful to human health and the environment. Tang et al. (2024) [12] collected FPW samples from the upper Yangtze River region and detected 55 trace heavy metals. With the exception of Mn, concentrations of all heavy metal elements in the samples—particularly the first-class pollutants—were found to be below the discharge limits specified in the Integrated Wastewater Discharge Standard. Xu et al. (2018) [89] investigated heavy metal contamination and leaching toxicity of oil-based drill cuttings in shale gas extraction, finding moderate heavy metal contamination and leaching toxicity well below standard values (China, GB 5085.3-2007) [90]. While heavy metal concentrations in groundwater associated with shale

oil and gas extraction have not reached standard pollution levels, they remain a significant concern for human health and require continued monitoring as key pollution indicators.

3.1.2. Sources of Inorganic Pollutants

The substantial volume of FPW generated by HF activities is a significant source of inorganic pollutants in shale gas development. These fluids contain elevated concentrations of inorganic constituents, including Na, Ca, Sr, Ba, and B. Some constituents, such as Ba, radioactive radium (Ra), B, and F, may exceed the World Health Organization (WHO) drinking water standards, posing significant health risks [19]. Additionally, these fluids contain trace elements like Cl, Br, and Li, as well as Sr and Mn, which may pose health risks [91]. Radionuclides, including Ra-226, Ra-228, and U-238, may infiltrate groundwater due to wellbore integrity issues. There are multiple potential sources of inorganic pollutants associated with shale gas development in shallow groundwater.

Natural sources: (1) Primary geochemical characteristics of shale formations. The dissolution of minerals within shale formations serves as a critical natural contributor to groundwater composition [19,92–94]. Heavy metals such as As, Cd, Ni, and Zn are released through the oxidation of sulfide minerals (e.g., pyrite) [10], while uranium oxides associated with organic matter may be liberated during the dissolution of carbonate minerals (e.g., calcite). Cation exchange sites on clay minerals (e.g., Ba^{2+}, Ra^{2+}) are prone to desorption under high-salinity conditions. Furthermore, deep-seated brines of evaporated seawater origin within sedimentary basins migrate upward through geological activities or fault systems, transporting characteristic components such as elevated concentrations of Na^{+}, Cl^{-}, Ba^{2+}, Sr^{2+}, and Ra [64,66,95]. **(2) Geochemical processes in shallow aquifers.** Redox-sensitive elements in shallow aquifers can be mobilized under specific environmental conditions [92,93,96–99]. Research indicates that Fe/Mn (oxyhydr)oxides dissolve under reducing conditions, releasing adsorbed elements such as As, Mo, Sb, and Se. Concurrently, the oxidation of organic matter facilitates the mobilization and migration of uranium [100]. These natural geochemical processes collectively define the baseline hydrogeochemical characteristics of groundwater in the study area.

Anthropogenic sources: (1) Shale gas development activities. Hydraulic fracturing FPW from shale gas operations exhibit distinctive high-salinity signatures (Na-Cl-type fluids with TDS reaching tens of thousands of ppm), enriched with characteristic elements including Ba, Sr, Ra, Li, and Br^{-}. Radionuclides such as Ra-226 and Ra-228 are predominantly derived from formation brines. Additionally, the oxidation of sulfides in drill cuttings can generate acid mine drainage (AMD), releasing heavy metals such as Cd, Pb, and Zn [89,101]. Under reducing conditions, $BaSO_4$ (barite) present in drilling waste dissolves, releasing Ba^{2+} and Ra^{2+}. **(2) Legacy contamination.** Historical oil and gas extraction activities in the study area may contribute to groundwater contamination through leaking-produced water or compromised well casings in abandoned oilfields, resulting in the upward migration of saline water containing Cl^{-}, Na^{+}, and Ba^{2+} [63,102]. Acidic mine drainage from coal mining operations typically contains elevated concentrations of SO_4^{2-}, Fe, Mn, and Al. **(3) Surface activity impacts.** Agricultural practices, including fertilizer application, promote NO_3^{-} leaching into aquifers, while domestic sewage increases NH_4^{+} levels [103,104].The Cl^{-}, Na^{+}, and Ca^{2+} can be introduced into groundwater systems by winter road de-icing agents (e.g., NaCl, $CaCl_2$) [19,105]. Landfill leachate further contributes Cl^{-}, organic pollutants, and reduced species such as Fe^{2+} and Mn^{2+} under anoxic conditions.

3.2. Organic Pollutants

3.2.1. Types of Organic Pollutants

Organic pollutants are the main constituents of FPW from shale gas extraction, characterized by a wide variety of types, low concentrations of individual components, and marked variability and uncertainty in their environmental impacts. These attributes not only dictate the potential environmental risks associated with FPW but also represent critical considerations in its storage, reuse, and treatment.

Extensive research has reported on the composition and characteristics of organic pollutants in FPW, with alkane compounds being the most prevalent. Wang et al. (2020) [106] analyzed FPW from the Changning shale gas area and found that straight-chain alkanes and cycloalkanes accounted for over 48% of the content. Similarly, Piotrowski et al. (2018) [107] reported that in FPW samples from the Marcellus shale region, alkanes made up 42% to 69% of the total organic content. Aromatic compounds are also a significant class of organic pollutants in FPW. Strong et al. (2014) [108] identified over 1000 organic compounds in FPW samples from Marcellus shale, with alkanes constituting about 50% of the identified organics, monocyclic aromatic compounds accounting for 26% to 27%, and polycyclic aromatic hydrocarbons (PAHs) representing 2% to 3%. He et al. (2018) [109] detected 13 parent PAHs and 4 alkyl-PAHs in FPW samples, primarily distributed in both the aqueous and particulate phases [110]. Additionally, halogenated organic compounds (HOCs) have garnered considerable attention due to their high concentrations in FPW and potential environmental impacts. Luek et al. (2017) [111] established the presence of a considerable number of HOCs in FPW using ultra-high-resolution Fourier transform ion cyclotron resonance mass spectrometry. Wang et al. (2020) [106] reported that HOCs in FPW from the Changning shale gas area in Sichuan were primarily chlorinated and brominated compounds. In contrast, the detection of functional groups such as alcohols, carboxylic acids, ethers, and epoxy compounds was less frequent. Tang et al. (2024) [12] analyzed and identified 45 to 104 volatile and semi-volatile organic compounds in samples of FPW from different shale gas fields in the upper Yangtze River, concluding that the primary pollutants in FPW are high-risk organics rather than heavy metals. Among the organic pollutants, aliphatic and aromatic compounds predominate, with oxygen- and nitrogen-substituted heteroatom compounds being prevalent. These research findings reveal the complexity and diversity of organic pollutants in FPW from shale gas development, where alkanes dominate, aromatic compounds and halogenated compounds are frequently detected, while the number of other functional groups is relatively limited.

3.2.2. Sources of Organic Pollutants

Fracking fluid additives: The additives in fracking fluids, including gelling agents, biocides, scale inhibitors, lubricants, and surfactants (Table 1), are among the primary sources of high-concentration dissolved organic carbon in FPW. Citric acid, used as an iron control agent in fracking fluids, was detected by Wolford (2011) [112] in FPW samples from the Marcellus shale region. Maguire-Boyle and Barron (2014) [113] identified fatty acids, phthalates, and phosphate esters in FPW, where fatty acids and phthalates are likely related to the use of drilling fluids and proppants, and phosphate esters are common lubricants. Phthalate compounds have been detected in multiple studies and are suspected to be associated with drilling fluids and proppants used in HF processes. Hoelzer et al. (2016) [114] detected multiple phthalates in FPW, suggesting that these compounds likely originate from flowback samples associated with HF activities. Lester et al. (2015) [115], in their analysis of FPW from the DJ Basin, identified organic pollutants from fracking fluid additives, including surfactants such as linear alkyl ethoxylates and elevated levels of acetic acid, a degradation byproduct of additives. Studies by Zhong et al. (2019) [116]

and He et al. (2018) [109] have identified polyethylene glycols (PEGs) and octylphenol ethoxylates (OPEs) in FPW from shale gas development, which are commonly used as surfactants in fracking fluids.

Geogenetic compounds: Additionally, organic pollutants in FPW are also derived from the dissolution of organic matter within shale formations and during prolonged contact with shale formations. Studies have indicated that the organic matter in geological strata primarily consists of alkanes, alkenes, aromatic hydrocarbons, phenols, and ketones [117]. Consequently, it is challenging to definitively source many of the organic compounds found in FPW. Ziemkiewicz and Thomas He (2015) [118] found that the concentrations of organic constituents collected during the flowback process exceed those in the injected fracking fluid, suggesting that the majority of components in FPW originate from the Marcellus shale formation rather than the fracking fluid itself.

Transformation products: When fracturing fluid and its additives are injected into shale formations under high pressure, they undergo physical and chemical changes in the downhole conditions of high temperature, high pressure, high salinity, and strong oxidizing agents. Hoelzer et al. (2016) [114] detected two classes of compounds in FPW that are almost certainly of geological origin: the archean core ether lipids and the pentacyclic terpenoids (i.e., hopanes). They also identified numerous transformation products in FPW samples and hypothesized the mechanisms of their abiotic transformation reactions, which include (a) delayed acid hydrolysis, (b) halogenation reactions, and (c) transformation reactions of additives. Luek et al. (2017) [111] discovered that the identified HOCs did not match any known additives, and no natural HOCs were found upon purification and analysis of shale formation water. During the reuse of FPW, when FPW is treated with chlorination for disinfection and subsequently reused as a fracking fluid, it can react with organic compounds in the wastewater to form disinfection byproducts, which may consequently be detected [106,107].

3.2.3. Hazards of Organic Pollutants

Refractory organic compounds in FPW, such as benzene series, PAHs, and heterocyclic compounds, pose risks of carcinogenicity, teratogenicity, and mutagenicity. PAHs, a class of persistent organic pollutants, are structurally stable and resistant to microbial degradation, exerting a strong inhibitory effect on microorganisms, which poses a severe threat to the survival of organisms and human health. Phenols and phthalates are highly toxic, carcinogenic, and mutagenic compounds capable of disrupting the endocrine system [119].

Among the myriad of organic substances present in FPW, particular concern is given to those with persistence, mobility, and toxicity (PMT), as well as very high persistence and very high mobility (vPvM). PMT and vPvM substances are characterized by their long environmental half-lives, an innate tendency to reach drinking water extraction points, difficulty in removal during water treatment processes, the highest potential for groundwater contamination, and the most challenging to remediate [120–123]. Huang et al. (2023) [124], through a literature review, identified 162 organic compounds in FPW and assessed that most of these compounds did not meet the PMT criteria, while 22 compounds met or were likely to meet PMT/vPvM criteria, necessitating priority risk management. These include 1,4-dioxane, anthracene, and 1,4-dichlorobenzene, among others. Wang et al. (2024) [125] employed a non-target screening strategy to detect and identify organic compounds in drilling fluids collected in the southwestern region of China. A total of 371 organic compounds were detected in the drilling fluids, predominantly consisting of heterocyclic compounds. A machine learning model was also utilized to identify 29 candidate PMT/vPvM substances, providing a priority list for early warning and risk assessment. These candidates were mainly derivatives of indene and naphthalene, such as indane, decahydronaphthalene,

1,2,3,4-tetrahydronaphthalene, and mesitylene, which are primarily sourced from the oil phase of the drilling fluids or natural materials from the shale formation.

4. Shale Gas Wastewater Treatment

Shale gas wastewater, in its broad definition, encompasses all wastewater generated throughout the entire extraction cycle of shale gas, including FPW, as well as wastewater from other stages. These wastewaters are characterized by high concentrations of dissolved solids, heavy metals, radioactive substances, and organic compounds. Appropriate treatment strategies and advanced treatment technologies can mitigate the potential threat of shale gas wastewater to groundwater by removing or reducing the concentration of harmful substances. This ultimately helps protect the groundwater environment in shale gas development areas.

4.1. Strategies of Shale Gas Wastewater Treatment

Initiating with basic separation to remove initial contaminants, shale gas wastewater undergoes primary treatment, followed by secondary and tertiary processes for further desalination and softening. Tailored treatment strategies are then selected based on specific objectives, including internal recycling, external reuse for agricultural irrigation, and deep well injection, ensuring effective management of the wastewater to minimize environmental impact (Figure 3).

4.1.1. Wastewater Reinjection

Deep well injection is a traditional method for managing FPW from HF by pressurizing and reinjecting the treated wastewater into specific geological layers. This approach is suitable for shale gas fields with accessible injectable strata to handle the wastewater generated from shale gas development, known as FPW. The reinjection process for FPW commonly includes stages such as oil removal, coagulation, sedimentation, flotation, and filtration (Figure 3), with details tailored to the specific conditions of the gas field. FPW is typically transported to on-site storage tanks around the wells and managed by third parties for disposal [126].

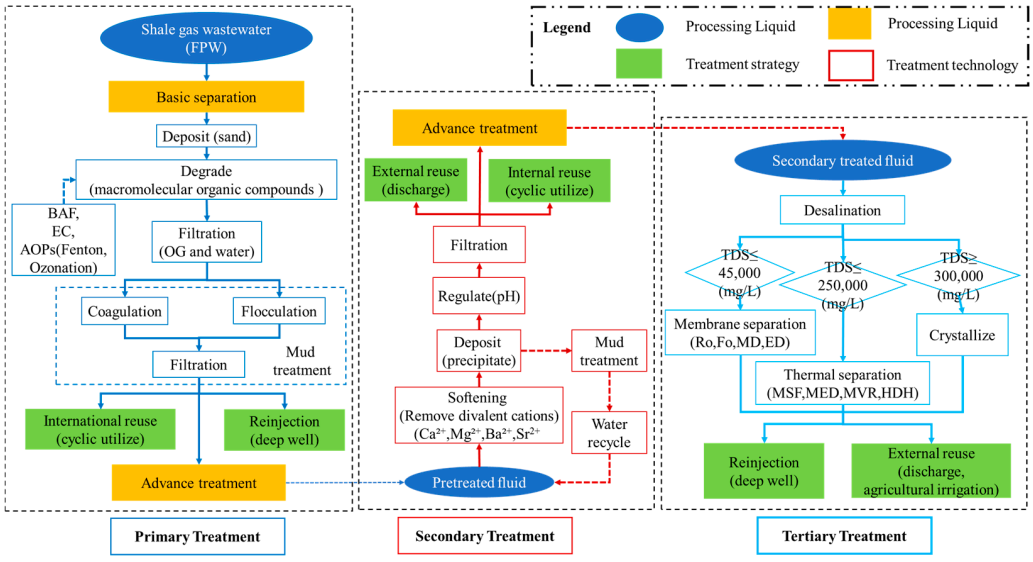


Figure 3. Comprehensive treatment process flowchart for shale gas extraction wastewater (modified from Zhao, 2023 [127]).

In the United States, wastewater reinjection has been the primary strategy for managing wastewater from shale gas operations. According to the Ground Water Protection

Council (GWPC), the injection rate of FPW from shale gas extraction has consistently exceeded 90% from 2007 to 2021. Data from 2021 show that 95.74% of the development wastewater was treated through underground injection, with half of it used for enhanced oil recovery. A small percentage, 1.2%, was discharged into water bodies or on the surface, 2.6% was sold or transferred for reuse within and outside the oil and gas industry for drilling and fracturing fluid in new wells, and 0.2% was evaporated through commercial treatment facilities in arid western states to avoid seismic risks associated with injection [69]. In China, early shale gas exploration and development also utilized wastewater reinjection. Flowback water from fracturing often relies on existing injection wells for treatment, requiring on-site pretreatment, dilution, blending with other water sources, and compatibility with additives to meet reinjection water quality standards. These standards include compliance with the "Gas Field Water Reinjection Method" (SY/T 6596—2004) [128], the "Unconventional Gas Field Produced Water Reinjection Environmental Protection Specification" (SY/T 7640—2021) [129], and considerations for sulfides, dissolved oxygen, and total iron [130].

The safety and feasibility of FPW reinjection remain contentious. While the reinjection of FPW appears low-risk, many uncharacterized mechanisms and long-term issues require ongoing monitoring and research. A deep well injection can induce seismic activity, potentially greater than HF-associated risks [131]. Limited availability of injection wells often leads to wastewater transfer between basins, increasing the environmental impact of transportation and the risks of incidents such as water and soil contamination from accidents or pipeline leaks [126]. Some injection wells, originally designed for conventional natural gas, do not meet the "same-layer reinjection" specification for shale gas FPW, leading to stratum instability, environmental risks, and long-term storage issues. This can also affect geothermal resource development in the injection layer, as seen in Zhaotong, Sichuan, where hot spring water development was impacted [132]. Many Chinese provinces, including Guizhou, Yunnan, and Chongqing, prohibit the reinjection of FPW. In Europe, deep well injections are illegal; for example, the UK prohibits underground reinjection of FPW, requiring FPW to be stored in closed steel containers on-site, while Germany reviews shale gas permits on a case-by-case basis [133]. The United States has established the "Underground Injection Control Program" to regulate wastewater reinjection from shale gas development. Therefore, as an environmental measure, the reinjection of oil and gas field produced water requires continuous updates to water quality indicators and environmental standards to adapt to new environmental requirements. It is also necessary to strengthen regulatory construction to ensure the safety and environmental sustainability of reinjection activities.

4.1.2. Wastewater Internal Reuse

The prevailing practice for treating shale gas wastewater involves the internal reuse of FPW, a strategy known as "internal reuse" [134,135]. This strategy reduces environmental impacts, lowers treatment costs, and decreases freshwater use in HF. However, repeated reuse can accumulate dissolved solids, leading to operational challenges. Over time, internal reuse has become widespread, with up to 90% of wastewater reused in HF operations, particularly in the Marcellus Shale, U.S. [126]. It is worth noting that as the shale gas industry matures and drilling rates decline, wastewater production will exceed reuse demands, necessitating desalination [74,136].

Evaluating water reuse requires defining effluent quality standards, which remain contentious due to a lack of universal guidelines [46,137]. Key parameters include TDS below 50,000–65,000 mg/L, chloride below 20,000–30,000 mg/L, TSS below 50 mg/L, pH 6–8, iron below 20 mg/L, total hardness below 2500 mg/L, oil and soluble organics below

25 mg/L, sulfate below 100 mg/L, and bacteria counts below 100 per 100 mL [135,138,139]. China's National Energy Industry Standards (NB/T14002.3-2022) [140] recommend total mineralization below 50,000 mg/L, total hardness below 2000 mg/L, iron below 10 mg/L, suspended solids below 1000 mg/L, and pH 6–9. In Chongqing's Nanchuan block, the treatment of FPW for reuse is subject to stringent criteria. FPW reuse requires transparency, stability, non-scaling properties, and compatibility to avoid precipitation or flocculation when mixed with other water sources [141].

Filtration is the standard pre-treatment for flowback water from HF, removing proppant and solids. This is followed by physical separation to eliminate suspended particles, mechanical impurities, and oil, along with pH adjustment to meet reuse criteria for Ca, Mg, Fe, and Cl concentrations (Figure 3). In the Fayetteville Shale, USA, low-salinity produced water is reused after filtration, mixed with fresh water to form fracturing fluid that meets quality standards [142]. Sedimentation and subsidence processes, such as open-air impoundments, improve produced water quality for reuse [46,60]. Coagulation and flocculation reduce TOC from 40 ppm to 5 ppm and iron from 22 ppm to 4 ppm. Chemical precipitation, including lime softening with $Ca(OH)_2$ and Na_2CO_3, effectively lowers total hardness below 2000 mg/L for reuse [138].

However, the repeated reuse of high-TDS water in HF increases salinity, altering fracturing fluid composition and reducing operational efficiency [82,143]. Liu et al. (2020) [144] found that gas wells fractured with saline recycled wastewater experienced a 20% drop in natural gas production compared to those using low-salinity water. High salinity also leads to insoluble carbonate or sulfate scale (e.g., Sr, Fe, Ba sulfates), which can deposit on wellbore walls, block fractures, and reduce gas production [145]. High TDS levels can also damage fracking pump seals [146] and affect fracturing fluid additive compatibility.

Optimizing on-site FPW treatment is crucial. This includes pH adjustment, coagulation/flocculation to remove suspended solids, colloidal particles, and NORM, as well as degreasing and deoiling (Figure 3). Effluent TDS and chloride levels must be assessed to determine suitability for reuse through dilution with fresh water [142]. Liang et al. (2018) [147] proposed a cost-effective treatment process using filtration, decolorization, and chelation, with optimized pH adjustment to ensure guar gum gelation and cross-linking properties, enabling flowback water reuse in arid regions.

4.1.3. Wastewater External Reuse

The external reuse of wastewater can support agricultural irrigation, livestock and wildlife drinking, human potable water, road dust suppression, firefighting, and industrial uses like power plant cooling. In the United States, there are documented cases of using FPW for irrigation and dust suppression, as well as treating coalbed methane extraction water for animal drinking [69,148]. However, high levels of organic pollutants and salinity in FPW hinder crop growth [149], requiring TDS reduction to below 3500 mg/L for normal plant development [150]. Chang et al. (2020) [151] explored fertilizer-driven forward osmosis (FDFO) technology for FPW purification, demonstrating its potential for agricultural irrigation in China. The nutrient-enriched diluted draw solution from FDFO promotes plant growth, offering a viable solution for irrigation systems. Despite this, China has limited applications of treated FPW for irrigation or livestock drinking.

Treated FPW can also be safely discharged into the environment if it meets national and local regulations. Offshore discharges are generally permitted if water quality standards are met, while onshore discharges are geographically restricted, typically in offshore platforms or desert gas fields [152]. In the U.S., about 1.2% of FPW was discharged in 2021, requiring treatment to meet National Pollutant Discharge Elimination System (NPDES) standards [69]. Effective discharge requires the removal of Chemical Oxygen

Demand (COD) and salts [153]. Establishing specialized FPW treatment facilities and using appropriate treatment processes for multi-stage treatment, including pretreatment, distillation, and membrane filtration (Figure 3), are the most effective methods to ensure compliance with environmental standards before discharge.

The valorization and recycling of FPW focus on extracting and utilizing its valuable components. Jang et al. (2017) [154] developed a method to recover Li from shale gas FPW, achieving a 41.2% extraction rate. Chang et al. (2019) [155] outlined techniques for recovering high-value elements like lithium, strontium, radium, uranium, and rare earth elements (REEs). Nanofiltration recovers lithium, membrane distillation/crystallization extracts strontium, and adsorption selectively isolates radium and uranium. Tian et al. (2020) [156] measured REE concentrations in FPW from China's Changning shale gas field, suggesting their recovery could offset processing costs. Yang et al. (2021) [157] employed an electrochemical method using a microbial desalination cell (MDC) with a poly (molybdate)/carbon black (PMo/CB) air cathode to recover ammonia and phosphorus from high-salinity FPW.

The external reuse of FPW offers significant potential for reducing environmental pollution and recovering resources. In the long term, treated discharge is the most promising approach, though it requires stricter water quality standards than reuse. However, challenges such as water quality standards, treatment costs, and equipment corrosion must be addressed. Feasibility depends on treatment capabilities, economic factors, and operational efficiency. Establishing standardized reuse criteria is crucial, as is integrating more efficient and practical treatment methods.

4.2. Technology of Shale Gas Wastewater Treatment

Shale gas extraction wastewater treatment can be categorized into three levels based on the treatment objectives and complexity of the process: primary pretreatment, secondary softening, and tertiary desalination (Figure 3) [127,158,159]. The primary level primarily utilizes physical separation techniques, focusing on phase separation, which includes processes such as centrifugation, coagulation/flocculation, flotation, and media filtration to remove suspended solids, oil and grease, and suspended organic matter. The secondary level employs chemical and biological methods to remove organic compounds, dissolved ions, and NORMs. The tertiary level, designed to address high-salinity wastewater, employs membrane and thermal technologies to eliminate TDS. In terms of practical treatment, it is challenging to achieve the recycling of FPW or meet the corresponding water quality standards relying solely on a single FPW treatment method. Generally, to ensure that the treated FPW conforms to the established water quality standards, a comprehensive treatment strategy should be employed [127,160].

4.2.1. Primary Treatment

Medium Filtration Techniques: Utilizing media such as walnut shells, sand, and anthracite, medium filtration effectively diminishes TOC and exceeds a 90% removal rate for OG, achieving near 100% water recovery. This method forgoes the need for wastewater pretreatment, remains unaffected by total dissolved solids (TDS) levels, and boasts low energy consumption. However, it necessitates the establishment of systems for media regeneration and spent media disposal, as highlighted by Igunnu and Chen (2014) [161].

Flotation Technology: Categorized based on bubble generation methods, this technology is divided into dissolved air flotation (DAF) and induced air flotation (IAF). DAF introduces inert gases like air or nitrogen to generate bubbles that target fine suspended solids. DAF, with a near 100% water recovery rate, removes fine suspended solids, OG, and volatile organic compounds (Table 3), with efficiency linked to bubble size [162]. Parker

and Monteith (1996) [163] observed that DAF performs optimally in wastewater with OG concentrations below 50 mg/L. It is capable of removing particles as large as 25 μm and, with coagulation pretreatment, can extend its reach to particles as small as 3–5 μm [164]. Lee et al. (2019) [165] reported an 86% OG removal rate in flowback water from the Changning shale gas field, which increased to 95.4% with coagulation–flocculation, underscoring the synergistic potential of these methods in low OG wastewater treatment.

Table 3. Treatment methods and water quality indicators for different contaminants.

Contaminant Type	Typical Substance	Water Quality Indicator	Treatment Method
Suspended Substance	Sand, foulant, bacteria	TSS; Turbidity	1. C-F and deposition/filtration
			2. MF/UF
Suspended Organic Matter	Oil, colloid, bacteria	OG; TOC; COD; BOD_5	1. Air flotation
			2. Adsorption (with activated carbon, zeolite)
			3. MF/UF
			4. Biodegradation
Dissolved Organic Matter	Benzene series, organic acid, phenols	BTEX; VOCs; Special chemical additives	1. Adsorption(with activated carbon, organic clay, zeolite, resin)
			2. C-F
			3. Chemical oxidation
			4. Biodegradation
			5. NF/RO
			6. Electrochemical treatment
Dissolved Polyvalent Metals and Anions	Fouling substance, natural radioactive material	Hardness; Specific metal ions (Fe, Sr, Ba); Specific anions (sulfates, nitrates)	1. Hardness: Ion exchange
			2. Metal: Deposition, filtration, ion exchange, RO
			3. Radioactive material: Ion exchange, RO
			4. Anions: Electrochemical, thermal treatment
Dissolved Monovalent Ions	Na^+, K^+, NH_4^+, Cl^-, I^-, NO_3^-	Specific ions (Na, Cl, Br); Ammonia	1. Thermal separation
			2. Membrane separation
			3. Electrochemical treatment

Coagulation–Flocculation (C-F): By incorporating coagulants and flocculants, this process destabilizes colloids and facilitates the flocculation and separation of pollutants utilizing mechanisms such as double layer compression, electrostatic neutralization, adsorption bridging, and sedimentation entrapment. It is lauded for its simplicity, efficacy, and cost-effectiveness, often serving as a preliminary step in the treatment of shale gas flowback water to diminish the load of organics and suspended solids (Table 3), thereby easing the burden on subsequent treatment stages. Nadella et al. (2020) [166] employed chlorine in conjunction with iron-based coagulants to treat high-salinity, high-turbidity flowback water from the Permian Basin, achieving remarkable removal rates of over 98% for turbidity and over 97% for total iron. Electrocoagulation (EC), an advanced coagulation technique, generates active coagulants in situ within flowback water, capitalizing on the high conductivity due to salinity to reduce treatment costs and enhance the removal of oil droplets [167–169]. Esmaeilirad et al. (2015) [170] reported that EC could remove over 60% of metal ions and over 95% of turbidity, showcasing its superiority in flowback water treatment. Zhang et al. (2020) [169] found EC to be significantly effective in removing hardness and turbidity, outperforming chemical coagulation and ultrafiltration, and indicating its promise in drilling wastewater treatment.

4.2.2. Secondary Treatment

Lime softening: Hydrated lime ($Ca(OH)_2$) or soda ash (Na_2CO_3) are used to reduce hardness levels (Ca^{2+}, Ba^{2+}, Mg^{2+}, Sr^{2+}). If hydrated lime is in sufficient quantity to raise the pH to alkaline levels (pH: ~10.3) then carbonate hardness and heavy metals like barium and strontium can precipitate. Insoluble barium compounds may be formed at low carbonate levels requiring coagulation and flocculation [158]. This is a low capital cost, proven and reliable technology.

Primary Oxidation Treatment: Primary oxidation employs oxidants like sodium hypochlorite and hydrogen peroxide to oxidize and remove high molecular weight organics from wastewater. This method demands substantial chemical input and regular equipment maintenance, yet it remains a critical step in wastewater management [127].

Advanced Oxidation Processes (AOPs): AOPs utilize highly reactive hydroxyl radicals for the rapid oxidation of refractory organics. Fenton oxidation, which uses iron salts to produce radicals, have been implemented in treating produced water from shale gas fields [127,171]. The COD removal rate of electro-Fenton oxidation is higher than that of conventional Fenton oxidation. Electro-oxidation offers broad applicability and efficiency but is susceptible to insulating layer formation [127,172]. It is effective when dealing with reflux fluids characterized by high salinity, high COD concentration, and intense coloration [173]. Ozonation combined with catalysts generates hydroxyl radicals for the degradation of aromatic compounds and other persistent organic pollutants. Photocatalytic oxidation relies on light to excite semiconductor materials, producing electron–hole pairs that trigger redox reactions and degrade pollutants in wastewater [174]. This technology is energy-efficient and capable of degrading a variety of targets but is limited by complex preparation and low treatment capacity.

Biological Treatment Technologies: These methods utilize microorganisms to degrade organic matter, offering a safe and sustainable solution without secondary pollution. Biological aerated filters (BAFs) and membrane bioreactors (MBRs) are prominent. BAFs, composed of permeable filtering media, form microbial communities on the media surface as wastewater flows through, removing TSS, COD, and nutrients effectively. MBRs combine biological treatment with membrane separation, enhancing sludge concentration and reducing treatment facility size [175,176]. Both technologies have demonstrated high removal rates for organic pollutants in flowback water [177,178]. Freedman et al. (2017) [179] reported the ABF treatment of FPW from the Denver–Julesburg basin, achieving over 90% and 80% removal rates for DOC and COD, respectively. Riley et al. (2016) [176] and Matsushita et al. (2018) [175] reported that aerobic MBRs can remove over 90% of six polycyclic aromatic hydrocarbons, including naphthalene and phenanthrene, from petrochemical wastewater, with removal mechanisms primarily involving biodegradation, volatilization, and adsorption.

Ion Exchange: Ion exchange resin technology is effective for metal ion removal, including natural radioactive ions, and serves as a pretreatment for membrane desalination [158,180]. Despite its high removal efficiency, the process is prone to scaling, and resin regeneration requires significant chemical use, increasing operational costs [181].

4.2.3. Tertiary Treatment

Membrane Separation Technologies: These technologies, encompassing microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), forward osmosis (FO), reverse osmosis (RO), electrodialysis (ED), and membrane distillation (MD), play a pivotal role in wastewater treatment [2]. MF, UF, and NF excel at removing suspended solids, colloids, bacteria, and viruses, with high efficiency in eliminating high molecular weight hydrocarbons and moderate effectiveness on low molecular weight organics. These processes are often em-

ployed as pretreatment steps for FO and RO. RO overcomes osmotic pressure by applying pressure, driving water across the membrane and separating it from salts. It is effective for wastewater with TDS below 40,000 mg/L, as demonstrated by a case in the Woodford shale gas field where RO reduced TDS from 13,833 mg/L to 128 mg/L, exceeding a 99% removal rate [182]. FO capitalizes on the osmotic pressure differences across a semipermeable membrane to drive water from the low-pressure side to the high-pressure side [135], achieving desalination, which is suitable for TDS below 35,000 mg/L. McGinnis et al. (2013) [183] have significantly reduced TDS concentrations in FPW from the Marcellus shale region using an NH_3/CO_2 FO desalination process. A combined FO and vacuum membrane distillation process developed by Li et al. (2014) [184] achieved nearly 90% water recovery from FPW in China. ED uses an electric field and ion exchange membranes to direct ion movement, separating and purifying wastewater, which is suitable for TDS up to 35,000 mg/L. Hao et al. (2015) [185] applied ED for the treatment of FPW, reporting removal efficiencies of 91% for most ions, with the exception of SO_4^{2-} (84.3%). MD relies on the vapor pressure difference across a hydrophobic porous membrane, allowing steam molecules to pass through and condense on the cold side, concentrating the solution. It is effective for TDS up to 250,000 mg/L, with Cho et al. (2018) [186] reporting removal rates of 86.3–91.7% for DOC and over 99.99% for TDS. These technologies demonstrate the efficiency and potential of membrane separation in treating FPW and recovering resources.

Capacitive Deionization (CDI): CDI, alternatively termed electrosorption technology (EST), achieves desalination by applying a low voltage to electrodes, prompting charged particles to migrate and adsorb on the electrodes due to electric and concentration gradients [187]. This method is effective for wastewater with TDS concentrations below 6000 mg/L. Despite its potential, CDI remains largely in the research phase, with significant steps needed before it can be implemented on an industrial scale [188].

Thermal Separation Technologies: These technologies, including multi-stage flash (MSF), multi-effect distillation (MED), mechanical vapor recompression (MVR), and humidification dehumidification (HDH), are commonly used for their exceptional desalination capabilities [183]. However, their operational costs are significantly higher than those of RO due to high energy consumption [161,188]. MED involves the serial connection of evaporators to purify steam by heating wastewater [189], suitable for treating wastewater with TDS concentrations up to 100,000 mg/L. It is favored for its low pretreatment requirements, low labor costs, and adaptability to water quality variations, along with its flexible operation [188]. MSF utilizes low-grade waste heat to evaporate brine in a series of staged containers, producing high-quality freshwater through condensation. Effective for TDS concentrations below 40,000 mg/L, MSF is recognized for its mature technology, stable operation, and tolerance to feedwater quality, with low scaling tendencies. However, energy supply and high feedwater retention rates limit its broader application [190]. HDH, an emerging desalination technology, efficiently harnesses low-grade thermal energy, particularly solar power, by coupling the processes of humidification and dehumidification to enhance thermal efficiency [191]. Suitable for treating wastewater with TDS concentrations below 60,000 mg/L, HDH has been commercialized and applied to oil and gas produced water treatment [2]. Shalaby et al. (2021) [192] found that HDH systems integrated with solar energy can maintain TDS levels between 138 and 148 mg/L in produced water, reducing energy consumption by 65% compared to treating low-salinity water. MVR employs secondary steam from evaporators, compressing it with a compressor to increase pressure and temperature. This pressurized steam is then returned to the evaporator, providing heat for further evaporation while condensing, thus recovering the latent heat of the steam and improving thermal efficiency. MVR is suitable for treating wastewater with TDS concentrations up to 80,000 mg/L, offering flexibility, high thermal efficiency, compact

equipment, low scaling tendencies, and resistance to high-salinity feedwater [193,194]. Hayes et al. (2014) [195] reported that at the Maggie Spain Facility in the Barnett shale gas field, MVR reduced TDS from 49,550 mg/L to 171 mg/L and TSS from 1272 mg/L to 9 mg/L, achieving removal rates of over 99%.

5. Recommendations and Future Strategies

5.1. Optimization of Wellbore Integrity Design and Construction

Ensuring wellbore integrity is critical to preventing the contamination of groundwater systems by fracturing fluids and fugitive gases. This necessitates optimizing completion designs, conducting detailed geological surveys, implementing high-quality cementing operations, and establishing robust wellbore integrity monitoring systems (Figure 4). Under high-pressure conditions, wellbore designs must account for mechanical and thermal stresses on casing and cement rings, with high-strength, corrosion-resistant materials employed to maintain structural stability. Structural enhancements to the wellbore, such as improved casing designs and cement formulations, can enhance sealing and pressure resistance, thereby reducing the risk of failure under extreme conditions.

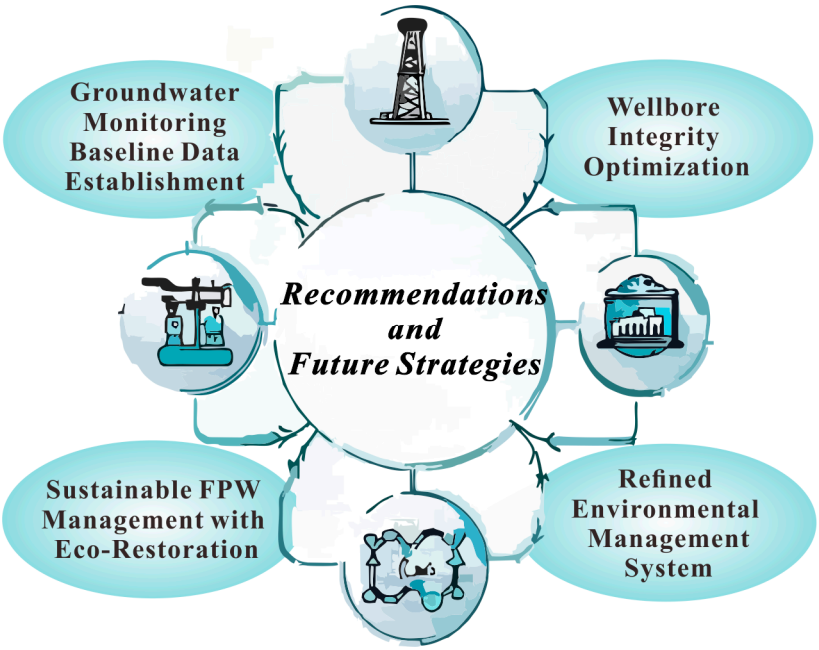


Figure 4. Recommendations and future strategies for the impact of shale gas development on groundwater.

Advanced geological survey techniques, such as high-density electrical methods and audio-frequency magnetotelluric sounding, must be employed to identify and avoid environmentally sensitive zones. High-performance cement systems and state-of-the-art cementing techniques should be utilized to ensure the integrity and sealing of the cement sheath. A comprehensive wellbore integrity monitoring system, integrating surface diagnosis, downhole detection, risk assessment, and management protocols, should be implemented to regularly inspect and address potential issues.

The continuous real-time monitoring of shale gas well production trends is essential for proactive risk management. Integrity testing and quantitative risk analysis can be achieved through technologies such as downhole acoustic and electromagnetic combined logging, as well as distributed optical fiber sensing. These methods enable early detection of potential leaks, allowing for timely corrective actions. Additionally, regular groundwater sampling and quality testing near extraction sites, combined with methane leakage monitoring

techniques, such as linear beam detection and leak detection and repair (LDAR), are critical for identifying and mitigating contamination risks. Such integrated approaches ensure both operational efficiency and environmental protection in shale gas development.

5.2. Sustainable FPW Management with Eco-Restoration

The effective management of FPW is achieved through the optimization of treatment processes, the adoption of innovative energy-efficient technologies (e.g., modular systems and microbial-based approaches), and the integration of renewable energy sources such as wind, solar, and geothermal power. These strategies are designed to reduce energy consumption and operational costs while improving treatment efficiency. Water resource reuse, including application for agricultural irrigation and industrial recycling, is combined with FPW recycling in fracturing operations to minimize freshwater demand and environmental impacts.

Nanomaterials are emerging as transformative tools in FPW treatment, offering superior performance over conventional methods. Their unique properties, including high surface area, strong adsorption capacity, and catalytic activity, enable effective removal of heavy metals, organic pollutants, and emerging contaminants. For instance, carbon-based nanomaterials such as graphene and carbon nanotubes exploit electrostatic interactions and hydrophobic effects to adsorb pollutants like perfluoroalkyl substances (PFAS) and arsenic. Metal oxide nanoparticles, such as Fe_3O_4 and TiO_2, facilitate photocatalytic degradation of recalcitrant compounds under UV light. These materials also synergize with membrane filtration and electrochemical processes, enhancing overall system efficiency.

Ecological restoration technologies, including engineered microbes, nanomaterials (e.g., nano-zero-valent iron), and phytoremediation, enable efficient FPW treatment. Future innovations in synthetic biology, AI monitoring, and hybrid systems with AOPs will enhance scalability, resource recovery (e.g., freshwater reuse), and sustainability while reducing environmental impacts.

5.3. Strengthening Groundwater Pollution Monitoring and Baseline Data Establishment

The development of robust environmental monitoring protocols for shale gas operations necessitates the establishment of comprehensive pre-drilling water quality baselines through systematic hydrogeochemical characterization. This foundational work involves extensive sampling and analysis of groundwater and surface water across multiple geological formations and hydrological regimes, with particular emphasis on quantifying background concentrations of hydrocarbon gases (including isotopic composition analysis via δ^{13}C-CH_4), major ions (Cl^-, Na^+, Ca^{2+}), and organic compounds. The resulting datasets should be integrated into geospatial databases to enable temporal and spatial trend analysis, providing critical reference points for subsequent environmental impact assessments.

A sophisticated monitoring framework must be implemented to track both conventional water quality parameters and shale gas-specific contaminants, including characteristic inorganic tracers (Br^-, B, Ba^{2+}, Sr^{2+}) and organic constituents such as BTEX compounds. Modern monitoring approaches should incorporate real-time sensor networks for continuous measurement of critical indicators (conductivity, dissolved gases), complemented by periodic laboratory analysis using advanced analytical techniques like gas chromatography-mass spectrometry. Automated data transmission systems ensure the timely detection of anomalous conditions. It is noteworthy that the current number of groundwater wells near shale gas extraction sites is often inadequate. Consequently, the installation of additional monitoring wells may be required to gather sufficient groundwater data. In areas with potential contamination risks, high-density well coverage is essential, particularly in structural fault zones that may act as preferential pathways for the migration of deep fluids.

The integration of these monitoring components with predictive modeling tools enables proactive environmental management, where machine learning algorithms process multivariate datasets to identify potential contamination events before regulatory thresholds are exceeded. This comprehensive approach, combining rigorous baseline characterization with state-of-the-art monitoring technologies, establishes a scientifically defensible framework for protecting water resources throughout the shale gas development lifecycle. The systematic collection and analysis of hydrochemical data not only supports regulatory compliance but also provides valuable insights for optimizing operational practices and mitigating potential environmental impacts.

5.4. Establishment of a Refined Environmental Management System

A refined environmental management system, incorporating international best practices such as wastewater discharge prohibition, downhole injection control, and fracturing fluid disclosure, is critical for sustainable industrial operations. Clear standards and technical specifications must be established for FPW treatment and fugitive gas control, with robust enforcement and monitoring mechanisms. Regulatory approaches to spill reporting and monitoring frequency vary between the U.S. EPA and China. While the U.S. adopts state-specific thresholds (e.g., Kentucky mandates all spill reports), China relies on nationally defined guidelines adaptable to local conditions. Similarly, the EPA enforces continuous emission monitoring with strict data requirements, whereas China's Sichuan Basin adjusts monitoring frequencies based on regional environmental needs and industry practices. These differences highlight the need for context-sensitive regulatory frameworks to balance environmental protection and operational feasibility.

An efficient environmental regulatory system, incorporating permanent hydrological wells monitoring and real-time water quality monitor inspections, can enhance oversight. It is worth noting that implementation barriers such as construction costs and regulatory capacity need to be taken seriously, as only a healthy, sustainable, and operational system can play the best regulatory role. At the same time, the conflict of interest of oil enterprise cannot be ignored. Developing an environmental risk assessment and early warning mechanism, along with robust emergency response plans, ensures preparedness for potential environmental issues. Clean fracturing technologies, such as liquefied CO_2 fracturing and petroleum gas fracturing, reduce water dependency and environmental impact. Environmentally friendly fracturing fluid systems minimize the use of harmful substances, lowering groundwater contamination risks.

Water resource management policies should prioritize alternative sources such as industrial wastewater, FPW, and high-salinity brine to reduce freshwater dependency. Development plans must align with regional water resource availability to promote sustainability. Transparency in water usage, achieved through monitoring and public reporting, fosters accountability and public trust.

6. Conclusions

The exploration and extraction of shale gas, while pivotal for meeting global energy demands, present significant challenges to groundwater quality. This study has systematically analyzed the various stages of shale gas development, identifying potential contamination pathways and the types of pollutants involved. Inorganic pollutants such as heavy metals and radionuclides, along with organic compounds like hydrocarbons, pose substantial risks to groundwater systems. The research underscores the importance of optimizing wellbore integrity, enhancing flowback fluid treatment, and implementing advanced wastewater management strategies to mitigate these risks.

The evaluation of current treatment technologies reveals that while methods like reinjection and internal reuse are effective, they are not without limitations. Advanced desalination and oxidation processes offer promising solutions but require further refinement to enhance efficiency and cost-effectiveness. The establishment of a comprehensive environmental management system, incorporating real-time monitoring and stringent regulatory frameworks, is crucial for minimizing environmental impacts.

Moreover, the integration of clean fracturing technologies and renewable energy sources can significantly reduce the environmental footprint of shale gas operations. The development of robust baseline data and pollution monitoring systems is essential for early detection and mitigation of contamination risks. This study concludes that sustainable shale gas development is achievable through the adoption of innovative technologies, rigorous environmental management practices, and continuous research and development. By prioritizing groundwater protection, the shale gas industry can contribute to global energy security while safeguarding vital water resources for future generations.

Funding: This study was funded by the Chongqing Postdoctoral Research Special Funding Project (2023CQBSHTB3158), Special for performance incentive and guidance of Chongqing research institutions (CSTB2023JXJL-YFX0075), Chongqing talent plan "Contract system project" (cstc2024ycjh-bgzxm0193) and the Open Project of National and Local Joint Engineering Research Center of Shale Gas Exploration and Development, Chongqing Institute of Geology and Mineral Resources (Project No. YYQKTKFGJDFLHGCYJZX-201903).

Conflicts of Interest: Author Dongxin Guo was employed by the company Chongqing Huadi Resources and Environment Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Howarth, R.W.; Ingraffea, A.; Engelder, T. Should Fracking Stop? *Nature* **2011**, *477*, 271–275. [CrossRef] [PubMed]
2. Zhou, S.; Huang, L.; Wang, G.; Wang, W.; Zhao, R.; Sun, X.; Wang, D. A Review of the Development in Shale Oil and Gas Wastewater Desalination. *Sci. Total Environ.* **2023**, *873*, 162376. [CrossRef] [PubMed]
3. Chen, Y.; Li, J.; Lu, H.; Xia, J. Tradeoffs in Water and Carbon Footprints of Shale Gas, Natural Gas, and Coal in China. *Fuel* **2020**, *263*, 116778. [CrossRef]
4. Zhang, K.; Yuan, X.; Han, F. Editorial: Reservoir Formation Conditions and Enrichment Mechanisms of Shale Oil and Gas. *Front. Earth Sci.* **2023**, *10*, 1047581. [CrossRef]
5. Zhu, B.; Meng, J.; Pan, R.; Hu, H.; Song, C.; Zhu, Z.; Jin, J. New Insights into the Evaluation Criteria for High-Quality Deep Marine Shale Gas Reservoirs in the Longmaxi Formation: Evidence from Organic Matter Pore Development Characteristics. *Front. Ecol. Evol.* **2023**, *11*, 1138991. [CrossRef]
6. Mukuhira, Y.; Fehler, M.C.; Ito, T.; Asanuma, H.; Häring, M.O. Injection-Induced Seismicity Size Distribution Dependent on Shear Stress. *Geophys. Res. Lett.* **2021**, *48*, e2020GL090934. [CrossRef]
7. Hagos, F.Y.; Abd Aziz, A.R.; Zainal, E.Z.; Mofijur, M.; Ahmed, S.F. Recovery of Gas Waste from the Petroleum Industry: A Review. *Environ. Chem. Lett.* **2022**, *20*, 263–281. [CrossRef]
8. Harkness, J.S.; Darrah, T.H.; Warner, N.R.; Whyte, C.J.; Moore, M.T.; Millot, R.; Kloppmann, W.; Jackson, R.B.; Vengosh, A. The Geochemistry of Naturally Occurring Methane and Saline Groundwater in an Area of Unconventional Shale Gas Development. *Geochim. Cosmochim. Acta* **2017**, *208*, 302–334. [CrossRef]
9. Huang, T.; Pang, Z.; Li, Z.; Li, Y.; Hao, Y. A Framework to Determine Sensitive Inorganic Monitoring Indicators for Tracing Groundwater Contamination by Produced Formation Water from Shale Gas Development in the Fuling Gasfield, SW China. *J. Hydrol.* **2020**, *581*, 124403. [CrossRef]
10. Vengosh, A.; Jackson, R.B.; Warner, N.; Darrah, T.H.; Kondash, A. A Critical Review of the Risks to Water Resources from Unconventional Shale Gas Development and Hydraulic Fracturing in the United States. *Environ. Sci. Technol.* **2014**, *48*, 8334–8348. [CrossRef]
11. Danforth, C.; Chiu, W.A.; Rusyn, I.; Schultz, K.; Bolden, A.; Kwiatkowski, C.; Craft, E. An Integrative Method for Identification and Prioritization of Constituents of Concern in Produced Water from Onshore Oil and Gas Extraction. *Environ. Int.* **2020**, *134*, 105280. [CrossRef] [PubMed]

12. Tang, P.; Shu, J.; Xie, W.; Su, Y.; He, Q.; Liu, B. Characterizing Hazardous Substances of Shale Gas Wastewater from the Upper Yangtze River: A Focus on Heavy Metals and Organic Compounds. *J. Hazard. Mater.* **2024**, *469*, 133873. [CrossRef] [PubMed]
13. Kondash, A.J.; Albright, E.; Vengosh, A. Quantity of Flowback and Produced Waters from Unconventional Oil and Gas Exploration. *Sci. Total Environ.* **2017**, *574*, 314–321. [CrossRef]
14. Zou, C.; Ni, Y.; Li, J.; Kondash, A.; Coyte, R.; Lauer, N.; Cui, H.; Liao, F.; Vengosh, A. The Water Footprint of Hydraulic Fracturing in Sichuan Basin, China. *Sci. Total Environ.* **2018**, *630*, 349–356. [CrossRef]
15. He, X.; Li, P.; Shi, H.; Xiao, Y.; Guo, Y.; Zhao, H. Identifying Strontium Sources of Flowback Fluid and Groundwater Pollution Using 87Sr/86Sr and Geochemical Model in Sulige Gasfield, China. *Chemosphere* **2022**, *306*, 135594. [CrossRef] [PubMed]
16. Xie, W.; Tian, L.; Tang, P.; Cui, J.; Wang, T.; Zhu, Y.; Bai, Y.; Tiraferri, A.; Crittenden, J.C.; Liu, B. Shale Gas Wastewater Characterization: Comprehensive Detection, Evaluation of Valuable Metals, and Environmental Risks of Heavy Metals and Radionuclides. *Water Res.* **2022**, *220*, 118703. [CrossRef]
17. Burden, S.; Cluff, M.A.; DeHaven, L.E.; Roberts, C.; Sharkley, S.L.; Singer, A. *Review of State and Industry Spill Data: Characterization of Hydraulic Fracturing-Related Spills*; U.S. Environmental Protection Agency Office of Research and Development: Washington, DC, USA, 2015.
18. Hill, C.B.; Yadav, O.P.; Khan, E. Examining Hydraulic Fracturing Chemicals: A Temporal and Comparative Analysis. *Water Res.* **2022**, *208*, 117878. [CrossRef]
19. Bondu, R.; Kloppmann, W.; Naumenko-Dèzes, M.O.; Humez, P.; Mayer, B. Potential Impacts of Shale Gas Development on Inorganic Groundwater Chemistry: Implications for Environmental Baseline Assessment in Shallow Aquifers. *Environ. Sci. Technol.* **2021**, *55*, 9657–9671. [CrossRef]
20. Rashidi Gooya, H.; Katibeh, H.; Maleki, A. Forecasting Groundwater Fluctuations Caused by Earthquakes Using Fuzzy Logic and AHP Method: A Case Study from Iran. *Earth Sci. Inf.* **2024**, *17*, 2143–2158. [CrossRef]
21. Kim, J.; Kaown, D.; Park, I.-W.; Lee, K.-K. Hydrogeochemical and Microbial Signatures of Deep and Shallow Groundwater near the Enhanced Geothermal System in Response to the Earthquake. *Environ. Earth Sci.* **2023**, *82*, 87. [CrossRef]
22. Tasker, T.L.; Burgos, W.D.; Piotrowski, P.; Castillo-Meza, L.; Blewett, T.A.; Ganow, K.B.; Stallworth, A.; Delompré, P.L.M.; Goss, G.G.; Fowler, L.B.; et al. Environmental and Human Health Impacts of Spreading Oil and Gas Wastewater on Roads. *Environ. Sci. Technol.* **2018**, *52*, 7081–7091. [CrossRef]
23. Uliasz-Misiak, B.; Winid, B.; Lewandowska-Śmierzchalska, J.; Matuła, R. Impact of Road Transport on Groundwater Quality. *Sci. Total Environ.* **2022**, *824*, 153804. [CrossRef] [PubMed]
24. Forman, R.T.; Sperling, D.; Bissonette, J.A.; Clevenger, A.P.; Cutshall, C.D.; Dale, V.H.; Fahrig, L.; France, R.; Goldman, C.R.; Heanue, K.; et al. *Road Ecology: Science and Solutions*; Island Press: Washington, DC, USA, 2003; p. 482.
25. Piwnicki, P. Road Projects–Waters in the Reports on the Environmental Impact Assessment. *Bud. Archit.* **2016**, *15*, 31–39. [CrossRef]
26. Hossain, M.E.; Al-Majed, A.A. *Fundamentals of Sustainable Drilling Engineering*; John Wiley & Sons: Hoboken, NJ, USA, 2015.
27. Alkalbani, A.M.; Chala, G.T. A Comprehensive Review of Nanotechnology Applications in Oil and Gas Well Drilling Operations. *Energies* **2024**, *17*, 798. [CrossRef]
28. Berger, B.; Anderson, K. *Modern Petroleum: A Basic Primer of the Industry*; Oil & Gas Journal: Tulsa, OK, USA, 1981.
29. Pereira, L.B.; Sad, C.M.S.; Castro, E.V.R.; Filgueiras, P.R.; Lacerda, V. Environmental Impacts Related to Drilling Fluid Waste and Treatment Methods: A Critical Review. *Fuel* **2022**, *310*, 122301. [CrossRef]
30. Davies, R.J.; Almond, S.; Ward, R.S.; Jackson, R.B.; Adams, C.; Worrall, F.; Herringshaw, L.G.; Gluyas, J.G.; Whitehead, M.A. Oil and Gas Wells and Their Integrity: Implications for Shale and Unconventional Resource Exploitation. *Mar. Pet. Geol.* **2014**, *56*, 239–254. [CrossRef]
31. Lefebvre, R. Mechanisms Leading to Potential Impacts of Shale Gas Development on Groundwater Quality. *WIREs Water* **2017**, *4*, e1188. [CrossRef]
32. Bachu, S.; Valencia, R.L. Well Integrity Challenges and Risk Mitigation Measures. *Bridge* **2014**, *44*, 28–34.
33. Kiran, R.; Teodoriu, C.; Dadmohammadi, Y.; Nygaard, R.; Wood, D.; Mokhtari, M.; Salehi, S. Identification and Evaluation of Well Integrity and Causes of Failure of Well Integrity Barriers (A Review). *J. Nat. Gas Sci. Eng.* **2017**, *45*, 511–526. [CrossRef]
34. Dusseault, M.B.; Gray, M.N.; Nawrocki, P.A. Why Oilwells Leak: Cement Behavior and Long-Term Consequences. In Proceedings of the SPE International Oil & Gas Conference and Exhibition in China (IOGCEC), Beijing, China, 7–10 November 2000.
35. Qi, P.; Tang, Y.; Zhang, C. Review and Prospects of Groundwater Pollution Control in Shale Gas Exploitation. *Water Supply* **2021**, *21*, 4382–4390. [CrossRef]
36. Ibukun, M.; Elyan, E.; Amish, M.; Njuguna, J.; Oluyemi, G.F. A Review of Well Life Cycle Integrity Challenges in the Oil and Gas Industry and Its Implications for Sustained Casing Pressure (SCP). *Energies* **2024**, *17*, 5562. [CrossRef]
37. Nowamooz, A.; Lemieux, J.-M.; Molson, J.; Therrien, R. Numerical Investigation of Methane and Formation Fluid Leakage along the Casing of a Decommissioned Shale Gas Well. *Water Resour. Res.* **2015**, *51*, 4592–4622. [CrossRef]

38. Chen, W.; Wan, W.; Zhao, Y.; He, H.; Wu, Q.; Zhou, Y.; Xie, S. Mechanical Damage Evolution and Mechanism of Sandstone with Prefabricated Parallel Double Fissures under High-Humidity Condition. *Bull. Eng. Geol. Environ.* **2022**, *81*, 245. [CrossRef]
39. Chen, W.; Liu, J.; Liu, W.; Peng, W.; Zhao, Y.; Wu, Q.; Wang, Y.; Wan, W.; Li, S.; Peng, H.; et al. Lateral Deformation and Acoustic Emission Characteristics of Dam Bedrock under Various River Flow Scouring Rates. *J. Mater. Res. Technol.* **2023**, *26*, 3245–3271. [CrossRef]
40. Chen, W.; Liu, J.; Peng, W.; Zhao, Y.; Luo, S.; Wan, W.; Wu, Q.; Wang, Y.; Li, S.; Tang, X.; et al. Aging Deterioration of Mechanical Properties on Coal-Rock Combinations Considering Hydro-Chemical Corrosion. *Energy* **2023**, *282*, 128770. [CrossRef]
41. Flewelling, S.A.; Sharma, M. Constraints on Upward Migration of Hydraulic Fracturing Fluid and Brine. *Ground Water* **2014**, *52*, 9–19. [CrossRef]
42. Birdsell, D.T.; Rajaram, H.; Dempsey, D.; Viswanathan, H.S. Hydraulic Fracturing Fluid Migration in the Subsurface: A Review and Expanded Modeling Results. *Water Resour. Res.* **2015**, *51*, 7159–7188. [CrossRef]
43. Barati, R.; Liang, J. A Review of Fracturing Fluid Systems Used for Hydraulic Fracturing of Oil and Gas Wells. *J. Appl. Polym. Sci.* **2014**, *131*, 40735. [CrossRef]
44. Ferrer, I.; Thurman, E.M. Chemical Constituents and Analytical Approaches for Hydraulic Fracturing Waters. *Trends Environ. Anal. Chem.* **2015**, *5*, 18–25. [CrossRef]
45. Brannon, H.D.; Pulsinelli, R.J. Breaker Concentrations Required To Improve the Permeability of Proppant Packs Damaged by Concentrated Linear and Borate-Crosslinked Fracturing Fluids. *SPE Prod. Eng.* **1992**, *7*, 338–342. [CrossRef]
46. Gregory, K.B.; Vidic, R.D.; Dzombak, D.A. Water Management Challenges Associated with the Production of Shale Gas by Hydraulic Fracturing. *Elements* **2011**, *7*, 181–186. [CrossRef]
47. Stringfellow, W.T.; Domen, J.K.; Camarillo, M.K.; Sandelin, W.L.; Borglin, S. Physical, Chemical, and Biological Characteristics of Compounds Used in Hydraulic Fracturing. *J. Hazard. Mater.* **2014**, *275*, 37–54. [CrossRef]
48. Zoback, M.D.; Arent, D.J. Shale Gas: Development Opportunities and Challenges. *Bridge* **2014**, *44*, NREL/JA-6A50-61466.
49. Davies, R.J.; Mathias, S.A.; Moss, J.; Hustoft, S.; Newport, L. Hydraulic Fractures: How Far Can They Go? *Mar. Pet. Geol.* **2012**, *37*, 1–6. [CrossRef]
50. Lange, T.; Sauter, M.; Heitfeld, M.; Schetelig, K.; Brosig, K.; Jahnke, W.; Kissinger, A.; Helmig, R.; Ebigbo, A.; Class, H. Hydraulic Fracturing in Unconventional Gas Reservoirs: Risks in the Geological System Part 1. *Environ. Earth Sci.* **2013**, *70*, 3839–3853. [CrossRef]
51. Kissinger, A.; Helmig, R.; Ebigbo, A.; Class, H.; Lange, T.; Sauter, M.; Heitfeld, M.; Klünker, J.; Jahnke, W. Hydraulic Fracturing in Unconventional Gas Reservoirs: Risks in the Geological System, Part 2: Modelling the Transport of Fracturing Fluids, Brine and Methane. *Environ. Earth Sci.* **2013**, *70*, 3855–3873. [CrossRef]
52. Reagan, M.T.; Moridis, G.J.; Keen, N.D.; Johnson, J.N. Numerical Simulation of the Environmental Impact of Hydraulic Fracturing of Tight/Shale Gas Reservoirs on Near-surface Groundwater: Background, Base Cases, Shallow Reservoirs, Short-term Gas, and Water Transport. *Water Resour. Res.* **2015**, *51*, 2543–2573. [CrossRef]
53. Missimer, T.M.; Maliva, R.G. Hydraulic Fracturing in Southern Florida: A Critical Analysis of Potential Environmental Impacts. *Nat. Resour. Res.* **2020**, *29*, 3385–3411. [CrossRef]
54. Liu, Y.; Yang, D.; Bian, H. Quantifying Aquifer Contamination Risk from Casing Rupture Using Support Vector Machine: A Comprehensive Assessment. *Stoch. Environ. Res. Risk Assess.* **2024**, *38*, 923–936. [CrossRef]
55. Dusseault, M.; Jackson, R. Seepage Pathway Assessment for Natural Gas to Shallow Groundwater during Well Stimulation, in Production, and after Abandonment. *Environ. Geosci.* **2014**, *21*, 107–126. [CrossRef]
56. Gassiat, C.; Gleeson, T.; Lefebvre, R.; McKenzie, J. Hydraulic Fracturing in Faulted Sedimentary Basins: Numerical Simulation of Potential Contamination of Shallow Aquifers over Long Time Scales. *Water Resour. Res.* **2013**, *49*, 8310–8327. [CrossRef]
57. Flewelling, S.A.; Tymchak, M.P.; Warpinski, N. Hydraulic Fracture Height Limits and Fault Interactions in Tight Oil and Gas Formations. *Geophys. Res. Lett.* **2013**, *40*, 3602–3606. [CrossRef]
58. Rahm, B.G.; Vedachalam, S.; Bertoia, L.R.; Mehta, D.; Vanka, V.S.; Riha, S.J. Shale Gas Operator Violations in the Marcellus and What They Tell Us about Water Resource Risks. *Energy Policy* **2015**, *82*, 1–11. [CrossRef]
59. Hammond, P.A.; Wen, T.; Woda, J.; Oakley, D. Pathways and Environmental Impacts of Methane Migration: Case Studies in the Marcellus Shale, USA. *Geofluids* **2024**, *2024*, 9290873. [CrossRef]
60. Barbot, E.; Vidic, N.S.; Gregory, K.B.; Vidic, R.D. Spatial and Temporal Correlation of Water Quality Parameters of Produced Waters from Devonian-Age Shale Following Hydraulic Fracturing. *Environ. Sci. Technol.* **2013**, *47*, 2562–2569. [CrossRef]
61. Ni, Y.; Liu, S.; Li, L.; Zhang, B.; Yao, L.; Sui, J.; Chen, J. Geochemical Characteristics of Shale Gas Hydraulic Fracturing Flowback/Produced Water in Zheng'an Block, Northern Guizhou Province, China. *J. Nat. Gas Geosci.* **2024**, *9*, 27–37. [CrossRef]
62. Warner, N.R.; Darrah, T.H.; Jackson, R.B.; Millot, R.; Kloppmann, W.; Vengosh, A. New Tracers Identify Hydraulic Fracturing Fluids and Accidental Releases from Oil and Gas Operations. *Environ. Sci. Technol.* **2014**, *48*, 12552–12560. [CrossRef]
63. Ni, Y.; Zou, C.; Cui, H.; Li, J.; Lauer, N.E.; Harkness, J.S.; Kondash, A.J.; Coyte, R.M.; Dwyer, G.S.; Liu, D.; et al. Origin of Flowback and Produced Waters from Sichuan Basin, China. *Environ. Sci. Technol.* **2018**, *52*, 14519–14527. [CrossRef]

64. Warner, N.R.; Jackson, R.B.; Darrah, T.H.; Osborn, S.G.; Down, A.; Zhao, K.; White, A.; Vengosh, A. Geochemical Evidence for Possible Natural Migration of Marcellus Formation Brine to Shallow Aquifers in Pennsylvania. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 11961–11966. [CrossRef]
65. Bordeleau, G.; Rivard, C.; Lavoie, D.; Lefebvre, R.; Malet, X.; Ladevèze, P. Geochemistry of Groundwater in the Saint-Édouard Area, Quebec, Canada, and Its Influence on the Distribution of Methane in Shallow Aquifers. *Appl. Geochem.* **2018**, *89*, 92–108. [CrossRef]
66. Dong, Y.; Gao, J.; Liu, Y.; Tao, L.; Wu, J.; Zhu, P.; Huang, H.; Zheng, H.; Huang, T. Salinization of Groundwater in Shale Gas Extraction Area in the Sichuan Basin, China: Implications for Water Protection in Shale Regions with Well-Developed Faults. *Sci. Total Environ.* **2024**, *915*, 170065. [CrossRef]
67. U.S. EPA. *Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States (Final Report)*; U.S. Environmental Protection Agency: Washington, DC, USA, 2016.
68. Clancy, S.A.; Worrall, F.; Davies, R.J.; Gluyas, J.G. The Potential for Spills and Leaks of Contaminated Liquids from Shale Gas Developments. *Sci. Total Environ.* **2018**, *626*, 1463–1473. [CrossRef]
69. Jon, W.S. *US Produced Water Volumes & Management Practices in 2021*; Ground Water Protection Council: Oklahoma City, OK, USA, 2022.
70. Parker, K.M.; Zeng, T.; Harkness, J.; Vengosh, A.; Mitch, W.A. Enhanced Formation of Disinfection Byproducts in Shale Gas Wastewater-Impacted Drinking Water Supplies. *Environ. Sci. Technol.* **2014**, *48*, 11161–11169. [CrossRef]
71. Ni, Y.; Yao, L.; Sui, J.; Chen, J.; Liu, F.; Wang, F.; Zhu, G.; Vengosh, A. Shale Gas Wastewater Geochemistry and Impact on the Quality of Surface Water in Sichuan Basin. *Sci. Total Environ.* **2022**, *851*, 158371. [CrossRef]
72. Holzman, D.C. Methane Found in Well Water near Fracking Sites. *Environ. Health Perspect.* **2011**, *119*, a289. [CrossRef]
73. Jackson, R.B.; Vengosh, A.; Darrah, T.H.; Warner, N.R.; Down, A.; Poreda, R.J.; Osborn, S.G.; Zhao, K.; Karr, J.D. Increased Stray Gas Abundance in a Subset of Drinking Water Wells near Marcellus Shale Gas Extraction. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 11250–11255. [CrossRef]
74. Vidic, R.D.; Brantley, S.L.; Vandenbossche, J.M.; Yoxtheimer, D.; Abad, J.D. Impact of Shale Gas Development on Regional Water Quality. *Science* **2013**, *340*, 1235009. [CrossRef]
75. Woda, J.; Wen, T.; Oakley, D.; Yoxtheimer, D.; Engelder, T.; Castro, M.C.; Brantley, S.L. Detecting and Explaining Why Aquifers Occasionally Become Degraded near Hydraulically Fractured Shale Gas Wells. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 12349–12358. [CrossRef]
76. Chang, Y.; Huang, R.; Masanet, E. The Energy, Water, and Air Pollution Implications of Tapping China's Shale Gas Reserves. *Resour. Conserv. Recycl.* **2014**, *91*, 100–108. [CrossRef]
77. Vandecasteele, I.; Marí Rivero, I.; Sala, S.; Baranzelli, C.; Barranco, R.; Batelaan, O.; Lavalle, C. Impact of Shale Gas Development on Water Resources: A Case Study in Northern Poland. *Environ. Manag.* **2015**, *55*, 1285–1299. [CrossRef]
78. Guo, M.; Lu, X.; Nielsen, C.P.; McElroy, M.B.; Shi, W.; Chen, Y.; Xu, Y. Prospects for Shale Gas Production in China: Implications for Water Demand. *Renew. Sustain. Energy Rev.* **2016**, *66*, 742–750. [CrossRef]
79. Scanlon, B.R.; Reedy, R.C.; Male, F.; Walsh, M. Water Issues Related to Transitioning from Conventional to Unconventional Oil Production in the Permian Basin. *Environ. Sci. Technol.* **2017**, *51*, 10903–10912. [CrossRef] [PubMed]
80. Wang, J.; Liu, M.; Bentley, Y.; Feng, L.; Zhang, C. Water Use for Shale Gas Extraction in the Sichuan Basin, China. *J. Environ. Manag.* **2018**, *226*, 13–21. [CrossRef]
81. Nicot, J.-P.; Scanlon, B.R. Water Use for Shale-Gas Production in Texas, U.S. *Environ. Sci. Technol.* **2012**, *46*, 3580–3586. [CrossRef]
82. Schmid, K.; Yoxtheimer, D. Wastewater Recycling and Reuse Trends in Pennsylvania Shale Gas Wells. *Environ. Geosci.* **2015**, *22*, 115–125. [CrossRef]
83. Scanlon, B.R.; Reedy, R.C.; Nicot, J.P. Will Water Scarcity in Semiarid Regions Limit Hydraulic Fracturing of Shale Plays? *Environ. Res. Lett.* **2014**, *9*, 124011. [CrossRef]
84. Shih, J.-S.; Saiers, J.E.; Anisfeld, S.C.; Chu, Z.; Muehlenbachs, L.A.; Olmstead, S.M. Characterization and Analysis of Liquid Waste from Marcellus Shale Gas Development. *Environ. Sci. Technol.* **2015**, *49*, 9557–9565. [CrossRef]
85. Chang, H.; Li, T.; Liu, B.; Vidic, R.D.; Elimelech, M.; Crittenden, J.C. Potential and Implemented Membrane-Based Technologies for the Treatment and Reuse of Flowback and Produced Water from Shale Gas and Oil Plays: A Review. *Desalination* **2019**, *455*, 34–57. [CrossRef]
86. Wang, H.; Lu, L.; Chen, X.; Bian, Y.; Ren, Z.J. Geochemical and Microbial Characterizations of Flowback and Produced Water in Three Shale Oil and Gas Plays in the Central and Western United States. *Water Res.* **2019**, *164*, 114942. [CrossRef]
87. Zhang, Z.; Zhuang, Y.; Li, J.; Zhou, Z.; Chen, S. Feasibility Evaluation of the Treatment and Recycling of Shale Gas Produced Water: A Case Study of the First Shale Gas Field in the Eastern Sichuan Basin, China. *Environ. Sci. Water Res. Technol.* **2019**, *5*, 358–369. [CrossRef]
88. Abass, O.K.; Zhuo, M.; Zhang, K. Concomitant Degradation of Complex Organics and Metals Recovery from Fracking Wastewater: Roles of Nano Zerovalent Iron Initiated Oxidation and Adsorption. *Chem. Eng. J.* **2017**, *328*, 159–171. [CrossRef]

89. Xu, T.; Wang, L.; Wang, X.; Li, T.; Zhan, X. Heavy Metal Pollution of Oil-Based Drill Cuttings at a Shale Gas Drilling Field in Chongqing, China: A Human Health Risk Assessment for the Workers. *Ecotoxicol. Environ. Saf.* **2018**, *165*, 160–163. [CrossRef]
90. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, and State Environmental Protection Administration. *GB 5085.3-2007*; Identification Standard for Hazardous Wastes: Leaching Toxicity Identification. China Environmental Science Press: Beijing, China, 2007.
91. Zhang, H.; Zhou, X.; Wang, L.; Wang, W.; Xu, J. Concentrations and Potential Health Risks of Strontium in Drinking Water from Xi'an, Northwest China. *Ecotoxicol. Environ. Saf.* **2018**, *164*, 181–188. [CrossRef] [PubMed]
92. Harrison, A.L.; Jew, A.D.; Dustin, M.K.; Thomas, D.L.; Joe-Wong, C.M.; Bargar, J.R.; Johnson, N.; Brown, G.E.; Maher, K. Element Release and Reaction-Induced Porosity Alteration during Shale-Hydraulic Fracturing Fluid Interactions. *Appl. Geochem.* **2017**, *82*, 47–62. [CrossRef]
93. Dustin, M.K.; Bargar, J.R.; Jew, A.D.; Harrison, A.L.; Joe-Wong, C.; Thomas, D.L.; Brown, G.E.; Maher, K. Shale Kerogen: Hydraulic Fracturing Fluid Interactions and Contaminant Release. *Energy Fuels* **2018**, *32*, 8966–8977. [CrossRef]
94. Huang, T.; Li, Z.; Mayer, B.; Nightingale, M.; Li, X.; Li, G.; Long, Y.; Pang, Z. Identification of Geochemical Processes During Hydraulic Fracturing of a Shale Gas Reservoir: A Controlled Field and Laboratory Water-Rock Interaction Experiment. *Geophys. Res. Lett.* **2020**, *47*, e2020GL090420. [CrossRef]
95. Darrah, T.H.; Vengosh, A.; Jackson, R.B.; Warner, N.R.; Poreda, R.J. Noble Gases Identify the Mechanisms of Fugitive Gas Contamination in Drinking-Water Wells Overlying the Marcellus and Barnett Shales. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 14076–14081. [CrossRef] [PubMed]
96. Kreisserman, Y.; Emmanuel, S. Release of Particulate Iron Sulfide during Shale-Fluid Interaction. *Environ. Sci. Technol.* **2018**, *52*, 638–643. [CrossRef]
97. Pearce, J.K.; Turner, L.; Pandey, D. Experimental and Predicted Geochemical Shale-Water Reactions: Roseneath and Murteree Shales of the Cooper Basin. *Int. J. Coal Geol.* **2018**, *187*, 30–44. [CrossRef]
98. Mehta, N.; Kocar, B.D. Geochemical Conditions Conducive for Retention of Trace Elements and Radionuclides during Shale–Fluid Interactions. *Environ. Sci. Process. Impacts* **2019**, *21*, 1764–1776. [CrossRef]
99. Phan, T.T.; Hakala, J.A.; Sharma, S. Application of Isotopic and Geochemical Signals in Unconventional Oil and Gas Reservoir Produced Waters toward Characterizing in Situ Geochemical Fluid-Shale Reactions. *Sci. Total Environ.* **2020**, *714*, 136867. [CrossRef] [PubMed]
100. Phan, T.T.; Capo, R.C.; Stewart, B.W.; Graney, J.R.; Johnson, J.D.; Sharma, S.; Toro, J. Trace Metal Distribution and Mobility in Drill Cuttings and Produced Waters from Marcellus Shale Gas Extraction: Uranium, Arsenic, Barium. *Appl. Geochem.* **2015**, *60*, 89–103. [CrossRef]
101. Eitrheim, E.S.; May, D.; Forbes, T.Z.; Nelson, A.W. Disequilibrium of Naturally Occurring Radioactive Materials (NORM) in Drill Cuttings from a Horizontal Drilling Operation. *Environ. Sci. Technol. Lett.* **2016**, *3*, 425–429. [CrossRef]
102. Tisherman, R.; Bain, D.J. Alkali Earth Ratios Differentiate Conventional and Unconventional Hydrocarbon Brine Contamination. *Sci. Total Environ.* **2019**, *695*, 133944. [CrossRef]
103. Jackson, R.E.; Heagle, D.J. Sampling Domestic/Farm Wells for Baseline Groundwater Quality and Fugitive Gas. *Hydrogeol. J.* **2016**, *24*, 269–272. [CrossRef]
104. Iqbal, J.; Su, C.; Abbas, H.; Jiang, J.; Han, Z.; Baloch, M.Y.J.; Xie, X. Prediction of Nitrate Concentration and the Impact of Land Use Types on Groundwater in the Nansi Lake Basin. *J. Hazard. Mater.* **2025**, *487*, 137185. [CrossRef]
105. Dugan, H.A.; Arnott, S.E. The Ecosystem Implications of Road Salt as a Pollutant of Freshwaters. *Wiley Interdiscip. Rev. Water* **2023**, *10*, e1629. [CrossRef]
106. Wang, B.; Xiong, M.; Wang, P.; Shi, B. Chemical Characterization in Hydraulic Fracturing Flowback and Produced Water (HF-FPW) of Shale Gas in Sichuan of China. *Environ. Sci. Pollut. Res.* **2020**, *27*, 26532–26542. [CrossRef]
107. Piotrowski, P.K.; Weggler, B.A.; Yoxtheimer, D.A.; Kelly, C.N.; Barth-Naftilan, E.; Saiers, J.E.; Dorman, F.L. Elucidating Environmental Fingerprinting Mechanisms of Unconventional Gas Development through Hydrocarbon Analysis. *Anal. Chem.* **2018**, *90*, 5466–5473. [CrossRef]
108. Strong, L.C.; Gould, T.; Kasinkas, L.; Sadowsky, M.J.; Aksan, A.; Wackett, L.P. Biodegradation in Waters from Hydraulic Fracturing: Chemistry, Microbiology, and Engineering. *J. Environ. Eng.* **2014**, *140*, B4013001. [CrossRef]
109. He, Y.; Sun, C.; Zhang, Y.; Folkerts, E.J.; Martin, J.W.; Goss, G.G. Developmental Toxicity of the Organic Fraction from Hydraulic Fracturing Flowback and Produced Waters to Early Life Stages of Zebrafish (Danio Rerio). *Environ. Sci. Technol.* **2018**, *52*, 3820–3830. [CrossRef]
110. Wu, K.; Cui, W.; Ren, G.; An, J.; Zheng, K.; Zeng, X.; Ouyang, M.; Yu, Z. Organoiodines in Effluents of a Shale-Fracturing Wastewater Treatment Plant. *Environ. Chem. Lett.* **2023**, *21*, 1943–1949. [CrossRef]
111. Luek, J.L.; Schmitt-Kopplin, P.; Mouser, P.J.; Petty, W.T.; Richardson, S.D.; Gonsior, M. Halogenated Organic Compounds Identified in Hydraulic Fracturing Wastewaters Using Ultrahigh Resolution Mass Spectrometry. *Environ. Sci. Technol.* **2017**, *51*, 5377–5385. [CrossRef] [PubMed]

112. Wolford, R.A. *Characterization of Organics in the Marcellus Shale Flowback and Produced Waters*; The Pennsylvania State University: University Park, PA, USA, 2011.
113. Maguire-Boyle, S.J.; Barron, A.R. Organic Compounds in Produced Waters from Shale Gas Wells. *Environ. Sci. Process. Impacts* **2014**, *16*, 2237–2248. [CrossRef] [PubMed]
114. Hoelzer, K.; Sumner, A.J.; Karatum, O.; Nelson, R.K.; Drollette, B.D.; O'Connor, M.P.; D'Ambro, E.L.; Getzinger, G.J.; Ferguson, P.L.; Reddy, C.M.; et al. Indications of Transformation Products from Hydraulic Fracturing Additives in Shale-Gas Wastewater. *Environ. Sci. Technol.* **2016**, *50*, 8036–8048. [CrossRef]
115. Lester, Y.; Ferrer, I.; Thurman, E.M.; Sitterley, K.A.; Korak, J.A.; Aiken, G.; Linden, K.G. Characterization of Hydraulic Fracturing Flowback Water in Colorado: Implications for Water Treatment. *Sci. Total Environ.* **2015**, *512–513*, 637–644. [CrossRef] [PubMed]
116. Zhong, C.; Li, J.; Flynn, S.L.; Nesbø, C.L.; Sun, C.; Von Gunten, K.; Lanoil, B.D.; Goss, G.G.; Martin, J.W.; Alessi, D.S. Temporal Changes in Microbial Community Composition and Geochemistry in Flowback and Produced Water from the Duvernay Formation. *ACS Earth Space Chem.* **2019**, *3*, 1047–1057. [CrossRef]
117. Luek, J.L.; Gonsior, M. Organic Compounds in Hydraulic Fracturing Fluids and Wastewaters: A Review. *Water Res.* **2017**, *123*, 536–548. [CrossRef]
118. Ziemkiewicz, P.F.; Thomas He, Y. Evolution of Water Chemistry during Marcellus Shale Gas Development: A Case Study in West Virginia. *Chemosphere* **2015**, *134*, 224–231. [CrossRef]
119. Ayanda, O.S.; Olutona, G.O.; Olumayede, E.G.; Akintayo, C.O.; Ximba, B.J. Phenols, Flame Retardants and Phthalates in Water and Wastewater—A Global Problem. *Water Sci. Technol.* **2016**, *74*, 1025–1038. [CrossRef]
120. Hale, S.E.; Arp, H.P.H.; Schliebner, I.; Neumann, M. What's in a Name: Persistent, Mobile, and Toxic (PMT) and Very Persistent and Very Mobile (vPvM) Substances. *Environ. Sci. Technol.* **2020**, *54*, 14790–14792. [CrossRef] [PubMed]
121. Hale, S.E.; Arp, H.P.H.; Schliebner, I.; Neumann, M. Persistent, Mobile and Toxic (PMT) and Very Persistent and Very Mobile (vPvM) Substances Pose an Equivalent Level of Concern to Persistent, Bioaccumulative and Toxic (PBT) and Very Persistent and Very Bioaccumulative (vPvB) Substances under REACH. *Environ. Sci. Eur.* **2020**, *32*, 155. [CrossRef]
122. Jin, B.; Huang, C.; Yu, Y.; Zhang, G.; Arp, H.P.H. The Need to Adopt an International PMT Strategy to Protect Drinking Water Resources. *Environ. Sci. Technol.* **2020**, *54*, 11651–11653. [CrossRef]
123. Jin, B.; Han, M.; Huang, C.; Arp, H.P.H.; Zhang, G. Towards Improved Characterization of the Fate and Impact of Hydraulic Fracturing Chemicals to Better Secure Regional Water Quality. *Environ. Sci. Process. Impacts* **2022**, *24*, 497–503. [CrossRef]
124. Huang, C.; Jin, B.; Han, M.; Zhang, G.; Arp, H.P.H. Identifying Persistent, Mobile and Toxic (PMT) Organic Compounds Detected in Shale Gas Wastewater. *Sci. Total Environ.* **2023**, *858*, 159821. [CrossRef]
125. Wang, Z.; Han, M.; Jin, B. Identifying Candidate Persistent, Mobile, and Toxic (PMT) and Very Persistent and Very Mobile (vPvM) Substances in Shale Gas Drilling Fluids by Combining Nontarget Analysis and Machine Learning Model. *Environ. Sci. Technol. Lett.* **2024**, *11*, 114–121. [CrossRef]
126. Lutz, B.D.; Lewis, A.N.; Doyle, M.W. Generation, Transport, and Disposal of Wastewater Associated with Marcellus Shale Gas Development. *Water Resour. Res.* **2013**, *49*, 647–656. [CrossRef]
127. Zhao, T. Treatment Technology of Shale Gas Fracturing Flowback Fluid: A Mini Review. *Front. Energy Res.* **2023**, *11*, 1245552. [CrossRef]
128. National Development and Reform Commission. *SY/T 6596—2004*; Recommended Practice for Produced-Water Reinjection in Gas Field. Petroleum Industry Press: Beijing, China, 2004.
129. State Energy Administration. *SY/T 7640—2021*; Environmental Protection Specification for Produced Water Reinjection in Unconventional Gas Fields. Petroleum Industry Press: Beijing, China, 2021.
130. Guo, C.; Chang, H.; Liu, B.; He, Q.; Xiong, B.; Kumar, M.; Zydney, A.L. A Combined Ultrafiltration–Reverse Osmosis Process for External Reuse of Weiyuan Shale Gas Flowback and Produced Water. *Environ. Sci. Water Res. Technol.* **2018**, *4*, 942–955. [CrossRef]
131. Ellsworth, W.L. Injection-Induced Earthquakes. *Science* **2013**, *341*, 1225942. [CrossRef]
132. Xiang, L.; Huang, D.; Kang, J.; Xu, R. Study on the Status of Shale Gas Development Fracturing and Returning Liquid Treatment in Southwest China and Its Emission Standard. *Adv. Environ. Prot.* **2019**, *9*, 575–583. [CrossRef]
133. Olsson, O.; Weichgrebe, D.; Rosenwinkel, K.-H. Hydraulic Fracturing Wastewater in Germany: Composition, Treatment, Concerns. *Environ. Earth Sci.* **2013**, *70*, 3895–3906. [CrossRef]
134. Shaffer, D.L.; Arias Chavez, L.H.; Ben-Sasson, M.; Romero-Vargas Castrillón, S.; Yip, N.Y.; Elimelech, M. Desalination and Reuse of High-Salinity Shale Gas Produced Water: Drivers, Technologies, and Future Directions. *Environ. Sci. Technol.* **2013**, *47*, 9569–9583. [CrossRef] [PubMed]
135. Estrada, J.M.; Bhamidimarri, R. A Review of the Issues and Treatment Options for Wastewater from Shale Gas Extraction by Hydraulic Fracturing. *Fuel* **2016**, *182*, 292–303. [CrossRef]
136. Kargbo, D.M.; Wilhelm, R.G.; Campbell, D.J. Natural Gas Plays in the Marcellus Shale: Challenges and Potential Opportunities. *Environ. Sci. Technol.* **2010**, *44*, 5679–5684. [CrossRef]

137. Blauch, M.E.; Myers, R.R.; Moore, T.R.; Lipinski, B.A.; Houston, N.A. Marcellus Shale Post-Frac Flowback Waters—Where Is All the Salt Coming from and What Are the Implications? In Proceedings of the SPE Eastern Regional Meeting, Charleston, WV, USA, 23 September 2009; p. SPE-125740-MS.
138. Henderson, C.; Acharya, H.; Matis, H.; Kommepalli, H.; Moore, B.; Wang, H. *Cost Effective Recovery of Low-TDS Frac Flowback Water for Re-Use*; General Electric Co.: Boston, MA, USA, 2011; p. 1030557.
139. Keister, T. Conversion of Marcellus Production Wastewater into Salable Products. In Proceedings of the Shale Energy Engineering 2014, Pittsburgh, PA, USA, 21–23 July 2014; American Society of Civil Engineers: Pittsburgh, PA, USA, 2014; pp. 85–94.
140. National Energy Administration. *NB/T 14002.3-2022*; Shale Gas—Reservoir Stimulation—Part 3: Recycling and Disposal Methods of Fracturing Flowback Water. Petroleum Industry Press: Beijing, China, 2022.
141. Jin, Y.X.; Bao, K.; Peng, L.; Sun, J.R.; Chen, J.W.; Fan, X.J.; Xu, H. Sources Analysis and Treatment Measures of Shale Gas Well Wastewater in Southeast Chongqing Area. *Guangzhou Chem. Ind.* **2021**, *49*, 79–82.
142. Mantell, M.E. Produced Water Reuse and Recycling Challenges and Opportunities across Major Shale Plays. In Proceedings of the EPA Hydraulic Fracturing Study Technical Workshop, Oklahoma City, OK, USA, 29–30 March 2011; Volume 4.
143. Akob, D.M.; Mumford, A.C.; Orem, W.; Engle, M.A.; Klinges, J.G.; Kent, D.B.; Cozzarelli, I.M. Wastewater Disposal from Unconventional Oil and Gas Development Degrades Stream Quality at a West Virginia Injection Facility. *Environ. Sci. Technol.* **2016**, *50*, 5517–5525. [CrossRef]
144. Liu, D.; Li, J.; Zou, C.; Cui, H.; Ni, Y.; Liu, J.; Wu, W.; Zhang, L.; Coyte, R.; Kondash, A.; et al. Recycling Flowback Water for Hydraulic Fracturing in Sichuan Basin, China: Implications for Gas Production, Water Footprint, and Water Quality of Regenerated Flowback Water. *Fuel* **2020**, *272*, 117621. [CrossRef]
145. Zou, C.; Dong, D.; Wang, Y.; Li, X.; Huang, J.; Wang, S.; Guan, Q.; Zhang, C.; Wang, H.; Liu, H.; et al. Shale Gas in China: Characteristics, Challenges and Prospects (I). *Pet. Explor. Dev.* **2015**, *42*, 753–767. [CrossRef]
146. Ord, J. Strategies for Disposing Waste Water. In Proceedings of the UK Shale Gas Environmental Summit, London, UK, 27–28 October 2014.
147. Liang, T.; Shao, L.; Yao, E.; Zuo, J.; Liu, X.; Zhang, B.; Zhou, F. Study on Fluid-Rock Interaction and Reuse of Flowback Fluid for Gel Fracturing in Desert Area. *Geofluids* **2018**, *2018*, 8948961. [CrossRef]
148. Al-Ghouti, M.A.; Al-Kaabi, M.A.; Ashfaq, M.Y.; Da'na, D.A. Produced Water Characteristics, Treatment and Reuse: A Review. *J. Water Process Eng.* **2019**, *28*, 222–239. [CrossRef]
149. Yang, Y.; Tian, L.; Shu, J.; Wu, Q.; Liu, B. Potential Hazards of Typical Small Molecular Organic Matters in Shale Gas Wastewater for Wheat Irrigation: 2-Butoxyethanol and Dimethylbenzylamine. *Environ. Pollut.* **2024**, *340*, 122729. [CrossRef] [PubMed]
150. Pica, N.E.; Carlson, K.; Steiner, J.J.; Waskom, R. Produced Water Reuse for Irrigation of Non-Food Biofuel Crops: Effects on Switchgrass and Rapeseed Germination, Physiology and Biomass Yield. *Ind. Crops Prod.* **2017**, *100*, 65–76. [CrossRef]
151. Chang, H.; Liu, S.; Tong, T.; He, Q.; Crittenden, J.C.; Vidic, R.D.; Liu, B. On-Site Treatment of Shale Gas Flowback and Produced Water in Sichuan Basin by Fertilizer Drawn Forward Osmosis for Irrigation. *Environ. Sci. Technol.* **2020**, *54*, 10926–10935. [CrossRef]
152. Costa, T.C.; Hendges, L.T.; Temochko, B.; Mazur, L.P.; Marinho, B.A.; Weschenfelder, S.E.; Florido, P.L.; Da Silva, A.; Ulson De Souza, A.A.; Guelli Ulson De Souza, S.M.A. Evaluation of the Technical and Environmental Feasibility of Adsorption Process to Remove Water Soluble Organics from Produced Water: A Review. *J. Pet. Sci. Eng.* **2022**, *208*, 109360. [CrossRef]
153. Mauter, M.S.; Palmer, V.R. Expert Elicitation of Trends in Marcellus Oil and Gas Wastewater Management. *J. Environ. Eng.* **2014**, *140*, B4014004. [CrossRef]
154. Jang, E.; Jang, Y.; Chung, E. Lithium Recovery from Shale Gas Produced Water Using Solvent Extraction. *Appl. Geochem.* **2017**, *78*, 343–350. [CrossRef]
155. Chang, H.; Liu, B.; Crittenden, J.C.; Vidic, R.D. Resource Recovery and Reuse for Hydraulic Fracturing Wastewater in Unconventional Shale Gas and Oil Extraction. *Environ. Sci. Technol.* **2019**, *53*, 13547–13548. [CrossRef]
156. Tian, L.; Chang, H.; Tang, P.; Li, T.; Zhang, X.; Liu, S.; He, Q.; Wang, T.; Yang, J.; Bai, Y.; et al. Rare Earth Elements Occurrence and Economical Recovery Strategy from Shale Gas Wastewater in the Sichuan Basin, China. *ACS Sustain. Chem. Eng.* **2020**, *8*, 11914–11920. [CrossRef]
157. Yang, F.; Zhang, K.; Zhang, D.; Zhang, L.; Huang, Y. Treatment and Nutrient Recovery of Synthetic Flowback Water from Shale Gas Extraction by Air-cathode (PMo/CB) Microbial Desalination Cells. *J. Chem. Technol. Biotechnol.* **2021**, *96*, 262–272. [CrossRef]
158. Karapataki, C. Techno-Economic Analysis of Water Management Options for Unconventional Natural Gas Developments in the Marcellus Shale. Ph.D. Dissertation, Massachusetts Institute of Technology, Cambridge, MA, USA, 2012.
159. Mohammad-Pajooh, E.; Weichgrebe, D.; Cuff, G.; Tosarkani, B.M.; Rosenwinkel, K.-H. On-Site Treatment of Flowback and Produced Water from Shale Gas Hydraulic Fracturing: A Review and Economic Evaluation. *Chemosphere* **2018**, *212*, 898–914. [CrossRef] [PubMed]

160. Loh, W.H.; Cai, Q.Q.; Li, R.; Jothinathan, L.; Lee, B.C.Y.; Ng, O.H.; Guo, J.; Ong, S.L.; Hu, J.Y. Reverse Osmosis Concentrate Treatment by Microbubble Ozonation-Biological Activated Carbon Process: Organics Removal Performance and Environmental Impact Assessment. *Sci. Total Environ.* **2021**, *798*, 149289. [CrossRef]
161. Igunnu, E.T.; Chen, G.Z. Produced Water Treatment Technologies. *Int. J. Low-Carbon Technol.* **2014**, *9*, 157–177. [CrossRef]
162. Hayes, T.; Arthur, D. Overview of Emerging Produced Water Treatment Technologies. In Proceedings of the 11th Annual International Petroleum Environmental Conference, Albuquerque, NM, USA, 12–15 October 2004; Volume 201512.
163. Parker, W.; Monteith, H. Stripping of VOC's from Dissolved Air Flotation. *Environ. Prog.* **1996**, *15*, 73–81. [CrossRef]
164. Sattler, A.; Hightower, M.; Nenoff, T.; Pless, J.; Phillips, M.; Brister, B.; Arnold, R.; Cather, M.; McPherson, B. Managing Coal Bed Methane Produced Water for Beneficial Uses, Initially Using the San Juan and Raton Basins as a Model. In *Interim Progress Report Prepared for NETL*; Sandia National Laboratory: Albuquerque, NM, USA, 2004.
165. Lee, Y.; Cui, M.; Choi, J.; Jeong, Y.; Khim, J. Demonstration and Evaluation of Potential Configuration Options for Shale-Wastewater Treatment Plant by Combining Several Unit Processes. *J. Clean. Prod.* **2019**, *232*, 867–876. [CrossRef]
166. Nadella, M.; Sharma, R.; Chellam, S. Fit-for-Purpose Treatment of Produced Water with Iron and Polymeric Coagulant for Reuse in Hydraulic Fracturing: Temperature Effects on Aggregation and High-Rate Sedimentation. *Water Res.* **2020**, *170*, 115330. [CrossRef]
167. Brillas, E.; Sirés, I.; Oturan, M.A. Electro-Fenton Process and Related Electrochemical Technologies Based on Fenton's Reaction Chemistry. *Chem. Rev.* **2009**, *109*, 6570–6631. [CrossRef]
168. Moussa, D.T.; El-Naas, M.H.; Nasser, M.; Al-Marri, M.J. A Comprehensive Review of Electrocoagulation for Water Treatment: Potentials and Challenges. *J. Environ. Manag.* **2017**, *186*, 24–41. [CrossRef]
169. Zhang, H.; Luo, Z.; Zhang, X.; Liu, Y.; Chen, Y. Electro-Flocculation Pretreatment Experiments of Shale Gas Drilling Wastewater. *Nat. Gas Ind. B* **2020**, *7*, 309–316. [CrossRef]
170. Esmaeilirad, N.; Carlson, K.; Omur Ozbek, P. Influence of Softening Sequencing on Electrocoagulation Treatment of Produced Water. *J. Hazard. Mater.* **2015**, *283*, 721–729. [CrossRef]
171. Wang, J.; Tang, J. Fe-Based Fenton-like Catalysts for Water Treatment: Catalytic Mechanisms and Applications. *J. Mol. Liq.* **2021**, *332*, 115755. [CrossRef]
172. Wu, S.; Yin, X.; Liu, Z.; Zhang, W.; Huang, Y.; Dong, F.; Zhang, D. Electrolyte Flow-Driven Coupling of Oxygen Evolution Reaction and CO_2 Electroreduction for Promoting Selective HCOOH Production under Acidic Conditions. *ACS Sustain. Chem. Eng.* **2025**, *13*, 7062–7073. [CrossRef]
173. Luo, M.; Yang, H.; Wang, K.; Song, F.; He, Y.; Zhang, Y.; Zhong, C. Coupling Iron-Carbon Micro-Electrolysis with Persulfate Advanced Oxidation for Hydraulic Fracturing Return Fluid Treatment. *Chemosphere* **2023**, *313*, 137415. [CrossRef] [PubMed]
174. Yang, H.; Tang, X.; Li, R.; Liu, X.; Zhang, P.; Gong, Y. Tunable Microscopic Aggregation Morphology of α-Ni(OH)2 for Enhanced Photocatalytic Degradation of Fracturing Flowback Fluid with Ozone Synergy. *Front. Mater.* **2022**, *9*, 995276. [CrossRef]
175. Matsushita, S.; Komizo, D.; Cao, L.T.T.; Aoi, Y.; Kindaichi, T.; Ozaki, N.; Imachi, H.; Ohashi, A. Production of Biogenic Manganese Oxides Coupled with Methane Oxidation in a Bioreactor for Removing Metals from Wastewater. *Water Res.* **2018**, *130*, 224–233. [CrossRef]
176. Riley, S.M.; Oliveira, J.M.S.; Regnery, J.; Cath, T.Y. Hybrid Membrane Bio-Systems for Sustainable Treatment of Oil and Gas Produced Water and Fracturing Flowback Water. *Sep. Purif. Technol.* **2016**, *171*, 297–311. [CrossRef]
177. Zilverentant, A.; Van Nieuwkerk, A.; Vance, I.; Watlow, A.; Rees, M. Pilot-Scale Membrane Bioreactor Treats Produced Water. In *World Oil*; Gulf Publishing Co.: Houston, TX, USA, 2009.
178. Mozo, I.; Stricot, M.; Lesage, N.; Spérandio, M. Fate of Hazardous Aromatic Substances in Membrane Bioreactors. *Water Res.* **2011**, *45*, 4551–4561. [CrossRef]
179. Freedman, D.E.; Riley, S.M.; Jones, Z.L.; Rosenblum, J.S.; Sharp, J.O.; Spear, J.R.; Cath, T.Y. Biologically Active Filtration for Fracturing Flowback and Produced Water Treatment. *J. Water Process Eng.* **2017**, *18*, 29–40. [CrossRef]
180. Nadav, N. Boron Removal from Seawater Reverse Osmosis Permeate Utilizing Selective Ion Exchange Resin. *Desalination* **1999**, *124*, 131–135. [CrossRef]
181. Cooley, H.; Donnelly, K. Hydraulic Fracturing and Water Resources: What Do We Know and Need to Know? In *The World's Water: The Biennial Report on Freshwater Resources*; Island Press: Washington, DC, USA, 2014; pp. 63–81.
182. Zhang, D.; Che, Z.; Ding, A.; Peng, S.; Lu, P. Reviews and prospects of shale gas flowback and produced water treatment technology selection. *J. Saf. Environ.* **2021**, *21*, 2761–2773. [CrossRef]
183. McGinnis, R.L.; Hancock, N.T.; Nowosielski-Slepowron, M.S.; McGurgan, G.D. Pilot Demonstration of the NH_3/CO_2 Forward Osmosis Desalination Process on High Salinity Brines. *Desalination* **2013**, *312*, 67–74. [CrossRef]
184. Li, X.-M.; Zhao, B.; Wang, Z.; Xie, M.; Song, J.; Nghiem, L.D.; He, T.; Yang, C.; Li, C.; Chen, G. Water Reclamation from Shale Gas Drilling Flow-Back Fluid Using a Novel Forward Osmosis–Vacuum Membrane Distillation Hybrid System. *Water Sci. Technol.* **2014**, *69*, 1036–1044. [CrossRef] [PubMed]

185. Hao, H.; Huang, X.; Gao, C.; Gao, X. Application of an Integrated System of Coagulation and Electrodialysis for Treatment of Wastewater Produced by Fracturing. *Desalin. Water Treat.* **2015**, *55*, 2034–2043. [CrossRef]
186. Cho, H.; Choi, Y.; Lee, S. Effect of Pretreatment and Operating Conditions on the Performance of Membrane Distillation for the Treatment of Shale Gas Wastewater. *Desalination* **2018**, *437*, 195–209. [CrossRef]
187. Kalfa, A.; Shapira, B.; Shopin, A.; Cohen, I.; Avraham, E.; Aurbach, D. Capacitive Deionization for Wastewater Treatment: Opportunities and Challenges. *Chemosphere* **2020**, *241*, 125003. [CrossRef] [PubMed]
188. Lan, D.; Chen, M.; Liu, Y.; Liang, Q.; Tu, W.; Chen, Y.; Liang, J. Development of Shale Gas in China and Treatment Options for Wastewater Produced from the Exploitation: Sustainability Lessons from the United States. *J. Environ. Eng.* **2020**, *146*, 4020103. [CrossRef]
189. Al-Karaghouli, A.; Kazmerski, L.L. Energy Consumption and Water Production Cost of Conventional and Renewable-Energy-Powered Desalination Processes. *Renew. Sustain. Energy Rev.* **2013**, *24*, 343–356. [CrossRef]
190. Feria-Díaz, J.J.; López-Méndez, M.C.; Rodríguez-Miranda, J.P.; Sandoval-Herazo, L.C.; Correa-Mahecha, F. Commercial Thermal Technologies for Desalination of Water from Renewable Energies: A State of the Art Review. *Processes* **2021**, *9*, 262. [CrossRef]
191. Nabil, I.; Abdalla, A.M.; Mansour, T.M.; Shehata, A.I.; Dawood, M.M.K. Salinity Impacts on Humidification Dehumidification (HDH) Desalination Systems: Review. *Environ. Sci. Pollut. Res.* **2024**, *31*, 1907–1925. [CrossRef]
192. Shalaby, S.M.; Kabeel, A.E.; Moharram, B.M.; Fleafl, A.H. Experimental Study of Hybrid Solar Humidification Dehumidification System for Extremely Saline Water Desalination. *Energy Convers. Manag.* **2021**, *235*, 114021. [CrossRef]
193. Jamil, M.A.; Zubair, S.M. On Thermoeconomic Analysis of a Single-Effect Mechanical Vapor Compression Desalination System. *Desalination* **2017**, *420*, 292–307. [CrossRef]
194. Farahat, M.A.; Fath, H.E.S.; El-Sharkawy, I.I.; Ookawara, S.; Ahmed, M. Energy/Exergy Analysis of Solar Driven Mechanical Vapor Compression Desalination System with Nano-Filtration Pretreatment. *Desalination* **2021**, *509*, 115078. [CrossRef]
195. Hayes, T.D.; Halldorson, B.; Horner, P.H.; Ewing, J.J.R.; Werline, J.R.; Severin, B.F. Mechanical Vapor Recompression for the Treatment of Shale-Gas Flowback Water. *Oil Gas Facil.* **2014**, *3*, 54–62. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.