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Review

Suggestions on the Development of Environmental Monitoring Technology of CO_2 Geological Storage and Leakage under the Background of China's "Double-Carbon" Strategy

Yinan Cui [1,*], Jiajia Bai [2,*], Songlin Liao [1], Shengjiang Cao [1] and Fangzhi Liu [1]

[1] Sinopec East China Petroleum Bureau, Taizhou 225300, China
[2] School of Petroleum Engineering, Changzhou University, Changzhou 213164, China
* Correspondence: cuiyn1109.hdsj@sinopec.com (Y.C.); baijiajia@cczu.edu.cn (J.B.)

Abstract: With the proposal of China's national "double carbon" strategic goal, carbon capture, utilization and storage (CCUS) technology has attracted more and more attention. Due to the high cost, high energy consumption and high risk of CCUS technology, this technology is still in the initial stage of development in China. Among them, CO_2 geological storage is one of the risks, and the environmental monitoring technology of CO_2 storage leakage is particularly important in the large-scale popularization and application of CCUS technology in China. On the basis of extensive research on the related literature concerning CO_2 storage and leakage, this paper begins with the types and mechanisms of CO_2 storage, analyzes the ways and risks of CO_2 storage and leakage and then summarizes the existing environmental monitoring technologies of CO_2 geological storage and leakage. In the future, China can promote the progress of CO_2 geological storage monitoring technology and help achieve the goal of "double carbon" by strengthening the research on CO_2 storage mechanism and main control factors, perfecting the risk assessment method of CO_2 storage, constructing the monitoring technology system of the CO_2 storage life cycle, and standardizing the CO_2 storage risk response system.

Keywords: CCUS; geological storage of CO_2; storage leakage; environmental monitoring

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Citation: Cui, Y.; Bai, J.; Liao, S.; Cao, S.; Liu, F. Suggestions on the Development of Environmental Monitoring Technology of CO_2 Geological Storage and Leakage under the Background of China's "Double-Carbon" Strategy. *Atmosphere* **2023**, *14*, 51. https://doi.org/10.3390/atmos14010051

Academic Editors: Dimitra Karali, Panagiotis Grammelis and Panagiotis Boutikos

Received: 22 November 2022
Revised: 16 December 2022
Accepted: 21 December 2022
Published: 27 December 2022

1. Introduction

With the rapid development of the economy and the continuous upgrading of social activities, China is faced with the double challenges of coping with climate change and changing air quality. On 22 September 2020, since the president of China, Xi Jinping made a solemn promise to the whole world at the 75th UN General Assembly that "China will strive to reach the peak of CO_2 emissions by 2030, and strive to achieve the goal of carbon neutrality by 2060" [1], CO_2 emission reduction has attracted more and more attention in China. Investigation at home and abroad show that the technology to achieve large-scale CO_2 emission reduction can be divided into the following three categories: improving energy utilization efficiency and reducing energy consumption; using low-carbon or carbon-free energy such as nuclear energy, hydropower, renewable energy, etc. [2]; and using CCUS (CO_2 capture, utilization and storage) technology, which means capturing CO_2 from industrial emission sources and using it or injecting it into geological structures for storage so as to achieve CO_2 emission reduction. Among them, CCUS technology is considered to be the most advantageous large-scale emission reduction technology at present. According to the statistics of "Global Carbon Capture and Storage Status 2021" [3], as of 2021, there are 135 commercial CCS facilities, of which 27 facilities are in operation, 2 facilities have been suspended, 4 facilities are under construction, 44 facilities are in the early development stage and 58 facilities are in the late development stage (Figure 1). Although the total number of CCS facilities in operation or development has doubled compared with the statistical data in "Global Carbon Capture and Storage Status 2020" [4], there is still a huge gap between the number of CCS facilities and the reduction of global anthropogenic emissions to net zero. To control the global warming at 2 °C, it is necessary to increase the capacity of CCS facilities from 40 million tons/year to more than 560 million tons/year by 2050 [3].

Figure 1. Global CCS Project Distribution Map [3].

The high cost and high risk of CCUS technology are the bottlenecks that hinder its large-scale application. Among them, the safety of geological storage and its possible environmental problems are also the biggest concerns of the public and environmental protection departments for CCUS projects [5]. In the process of geological storage of CO_2, there are many and miscellaneous risks of CO_2 leakage, and once CO_2 leaks, it will cause certain harm to the ecological environment, so it is particularly important to carry out environmental monitoring of CO_2 storage leakage. North, Northeast, and Northwest China have good conditions for the geological utilization and storage of CO_2. The theoretical total capacity of onshore geological utilization and storage technology is 1.5×10^{12}~3.0×10^{12} t CO_2, and the theoretical storage capacity of the ocean is approximately one trillion tons. However, its research on CCUS technology is still in the initial stage. There is little research related to CO_2 storage monitoring, and most of it is aimed at specific storage sites. At present, there is no perfect standard for CO_2 storage monitoring. It is urgent to establish an all-time and multi-index CO_2 storage leakage monitoring system as soon as possible that integrates geophysical and chemical monitoring, wellbore integrity monitoring, atmospheric monitoring, groundwater monitoring, surface water monitoring and soil monitoring.

On the basis of summarizing the types and mechanisms of CO_2 geological storage, the ways and hazards of CO_2 geological storage leakage, and the existing environmental monitoring technologies of CO_2 storage leakage, combined with the development status of CCUS technology in China, this paper puts forward the next development suggestions of China's environmental monitoring technologies of CO_2 storage leakage under the background of "double carbon" and provides decision support for the realization of the "double carbon" strategic goal.

2. Types and Mechanisms of CO_2 Geological Storage

The geological storage of CO_2 is the process of storing CO_2 in underground reservoirs by means of engineering technology so as to avoid its emission into the atmosphere [6]. This technology is also the most economical and effective CO_2 storage technology at present. Figure 2 shows the geological storage potential [3]. Among various geological storage sites of CO_2, depleted oil and gas reservoirs, deep saline aquifers and deep unmanageable coal seams are considered the three most potential storage sites [7].

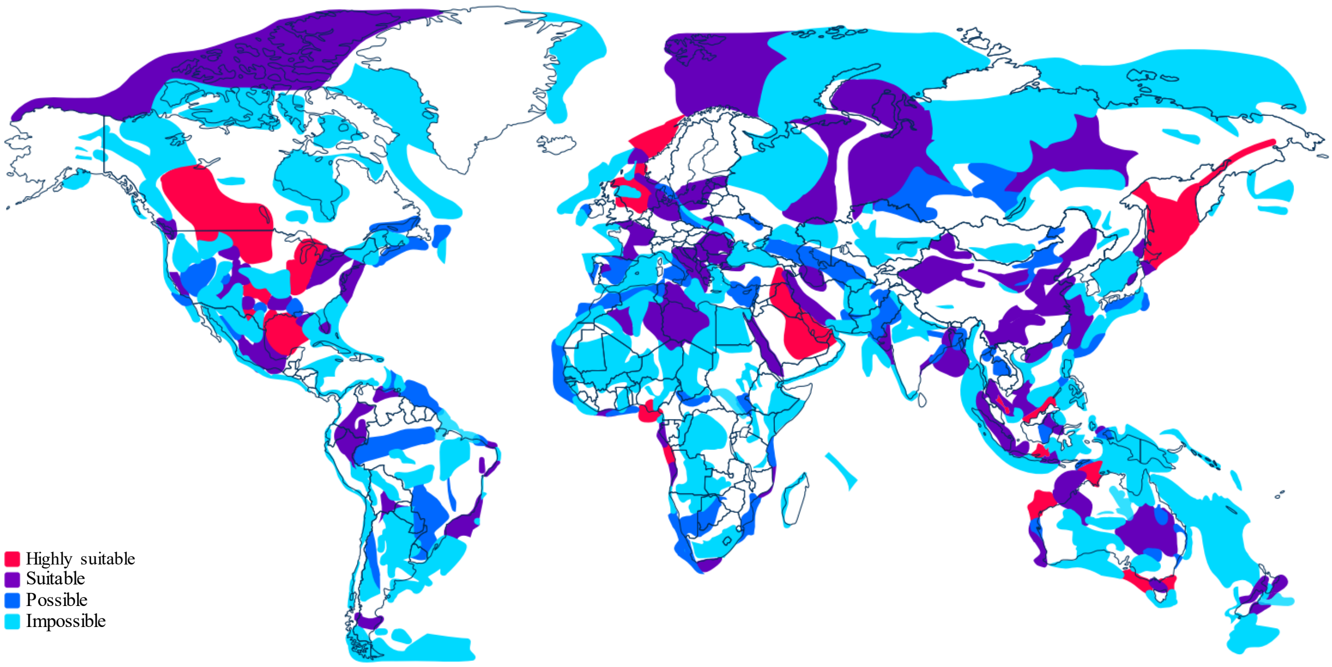

Figure 2. Distribution map of suitable storage areas in the world [3].

2.1. Types of CO_2 Geological Storage

2.1.1. Storage in Depleted Oil and Gas Reservoirs

The depleted oil and gas reservoir refers to the oil and gas reservoir whose remaining oil and gas cannot be extracted under certain economic and technical conditions, thus, losing its exploitation value [8]. Using depleted oil and gas reservoirs to carry out CO_2 geological storage can make full use of the existing oil and gas reservoir exploration and development data. It is because of this that the cost of preliminary research and evaluation is reduced. Depleted oil and gas reservoirs are early geological sites suitable for CO_2 storage.

The calculation of the storage capacity of depleted oil and gas reservoirs is mainly based on the material balance method, and its basic assumption is that all the space released by oil and gas exploitation can be used for CO_2 storage. In 2006, the calculation results of Liu et al. [9] showed that the geological storage of CO_2 in major oil-bearing basins in China was approximately 30.5×10^9 t.

2.1.2. Storage in Deep Saline Aquifers

The research of Zhang et al. [10] shows that a suitable large-scale CO_2 storage site in deep saline aquifers should have the characteristics of buried depth greater than 800 m, salinity of formation water between 10~50 g/L, good water resistance of top and bottom plates and so on. According to statistics, deep saline water storage accounts for approximately 98% of all storage sites, which is an ideal place for CO_2 storage [11].

According to the research results in "China's Annual Report on CO_2 Capture, Utilization and Storage (CCUS) (2021)" [12], the CO_2 storage capacity of deep saline aquifers in China is approximately 2420 billion tons, and its distribution is basically the same as that of oil-bearing basins. Among them, Songliao Basin, Tarim Basin and Bohai Bay Basin rank as the top three in China with the storage potential in the deep saline water layer of 694.5 billion tons, 552.8 billion tons and 490.6 billion tons, respectively. In addition, the storage capacity of deep saline aquifers in the northern Jiangsu basin is approximately

435.7 billion tons, and that in the Ordos area is approximately 335.6 billion tons, which also has great storage potential.

2.1.3. Storage in Deep Unmanageable Coal Seams

Coal seams have a large number of micro-pores that can absorb various gases. Because the adsorption capacity of CO_2 on the surface of the coal seam is approximately twice that of CH_4 [13], CO_2 can effectively replace CH_4 after it is injected into the coal seam. When CO_2 is stored in the coal seam, which cannot be mined conventionally because of the deep buried depth, it will realize the effective storage of CO_2 and the increase in coalbed methane production at the same time.

Deep coal seams are widely developed in China; therefore, they are a good geological body for the implementation of CO_2—ECBM (CO_2 displacement of coalbed methane CH_4). Li et al. [14] used the formula method to evaluate the CO_2 storage potential of multiple deep unmanageable coal seams in China. The evaluation results showed that the geological storage capacity of CO_2 in 45 major coal-bearing basins in China was approximately 120×10^8 t, and the storage potential was huge (Table 1).

Table 1. Geological storage of CO_2 in 45 major coal-bearing basins in China [14].

Coal-Bearing Region	Estimated Capacity/Mt	Coal-Bearing Region	Estimated Capacity/Mt
Ordos Basin and Hedong-Weibei	4450	Northern Tarim	36
Turpan-Hami Basin	2200	Northern Qaitam	30
Santang Lake	990	South Songliao	28
Eastern Junggar	650	Daqin-Wula Mountains	27
Qinshui Basin	610	Youerdusi	26
Ili Basin	560	Middle Qilian coal-bearing region	25
Northern Junggar	530	Dacheng	25
Southern Junggar	340	Jingyuan-Jingtai coal-bearing region	14
Sanjiang-Mulinhe	240	Northern Qilian coal-bearing region	11
Datong-Ningwu	160	Chengde	11
Yangi Basin	120	Dunhua-Fushun coal-bearing region	11
Huainan	120	Huayinshan-Yongrong	11
Liupanshui	110	Kunming Kaiyuan	10
Eastern Tarim	100	Beipiao Coal-bearing region	8
South Sichuan and North Guizhou	79	Jinan	7
Xuzhou-Huaibei	78	Fuxin-Zhangwu	7
Zhangjiakou	72	Yilan-Yitong	6
Western Shandong	68	Yanbian coal-bearing region	5
Western Henan	56	Baise Basin	5
Bejjing-Tangshan	55	Eastern Henan	4
Eastern Piedmont of Taihang Mountains	51	Middle Shandong	4
Xuanhua-Weixian	44	Lianyuan-Shaoyang	4
Zhuozi-Helan Mountains	38	Total storage capacity	12,000

2.2. Geological Storage Mechanisms of CO_2

Efficient CO_2 storage is realized under the joint action of physical, chemical and adsorption mechanisms, among which the physical storage mechanism of CO_2 mainly includes structural geological storage, binding storage and hydrodynamic storage, while the chemical storage mechanism mainly includes dissolution and mineralization storage, while the adsorption mechanism mainly occurs in coal seam storage [15].

2.2.1. Physical Storage Mechanism

(1) Structural geological storage

When the CO_2 is injected into the formation, it cannot flow due to the impermeable layer, which would form a structural trap. CO_2 will be permanently stored underground. This kind of storage mechanism is structural geological storage [16–18]. Structural geological storage, also known as static storage, is the most important mechanism in CO_2 storage [19].

(2) Binding storage

When CO_2 migrates in the formation, CO_2 is permanently trapped in the pores of rock particles due to capillary force and surface tension. This kind of storage mechanism is binding storage. In the process of geological storage, the binding gas-storage mechanism has the longest duration and, therefore, is the main storage mechanism [20].

(3) Hydrodynamic storage

If the reservoir in the deep saline aquifers is not completely closed and the fluid velocity is low, when CO_2 is injected into it, CO_2 will rise to the top of the aquifer under the action of buoyancy, while the extremely low underground water migration rate can ensure the long-term (geological time scale) storage of CO_2 in a reservoir [21,22].

2.2.2. Chemical Storage Mechanism

(1) Dissolution storage

CO_2 dissolves in underground fluid, and its degree of dissolution varies with temperature, pressure, salinity and CO_2 saturation [23]. The occurrence of dissolution mainly depends on the vertical permeability and thickness of the storage formation. Dissolving and storage would reduce the amount of free CO_2 and the risk of CO_2 migration and leakage; therefore, it is considered a type of relatively safe and stable storage.

(2) Mineralization storage

In the process of CO_2 storage, influenced by factors such as rock mineral composition and fluid type, CO_2 will chemically react with some components in rocks and groundwater, and then, carbonate mineralization will be generated. Mineralization is a mechanism of stable and long-term storage of CO_2, and its time scale is very long, usually taking hundreds to thousands of years to complete [24].

2.2.3. Adsorption Mechanism

The adsorption mechanism mainly occurs in coal seam storage. Coal seam surface pores have unsaturated energy. This makes it easy for the coal seam to generate van der Waals force with nonpolar molecules, thus, having adsorption capacity. Because the adsorption capacity of the coal seam for CO_2 is much higher than that of methane, injecting CO_2 into the coal seam for sequestration can successfully replace methane and realize CO_2 storage [25].

The geological storage of CO_2 is often the result of a multi-mechanism interaction. According to the physical and chemical characteristics of CO_2 and the characteristics of various geological storage bodies, the storage mechanisms of depleted oil and gas reservoirs are mainly structural geological storage, binding storage, dissolution storage and mineralization storage. The storage mechanisms of deep saline aquifers mainly include structural geological storage, binding storage, hydrodynamic storage, dissolution storage and mineralization storage. The storage mechanisms of deep unmanageable coal seam are mainly binding storage and coal seam adsorption storage [26].

3. Paths and Risks of CO_2 Storage Leakage

Realizing the safe and efficient storage of CO_2 is the eternal goal of CCUS technology. Once CO_2 leaks, it causes certain harm to the ecological environment, so it is necessary to analyze the leakage ways for CO_2 so as to better carry out the research on monitoring technology of CO_2 storage leakage. According to the research on the main geological storage types and storage mechanism of CO_2 in the second section, it is clear that the leakage paths of CO_2 storage mainly include the wellbore system, fault/fracture system and cap system [27].

3.1. Paths of CO_2 Storage Leakage

The wellbore is the only way to inject CO_2 into the formation. In the process of CO_2 geological storage, with the passage of time, on the one hand, the weak acid produced by CO_2 dissolution corrodes the casing and annulus. On the other hand, the temperature and pressure conditions change due to CO_2 injection, which makes the casing or cement sheath plastically deform and destroys the integrity of the wellbore [28,29].

When a large amount of CO_2 is injected into the formation, the high pressure will change the pressure balance of the formation, causing cracks to occur in caprock rocks, activity in the fault plane and activation of the originally closed fault, which greatly increases the leakage risk of CO_2 (Figure 3). Studies have shown the main factors affecting CO_2 leakage along faults and fractures are fracture opening, effective permeability, injection depth, injection speed and reservoir heterogeneity [30,31].

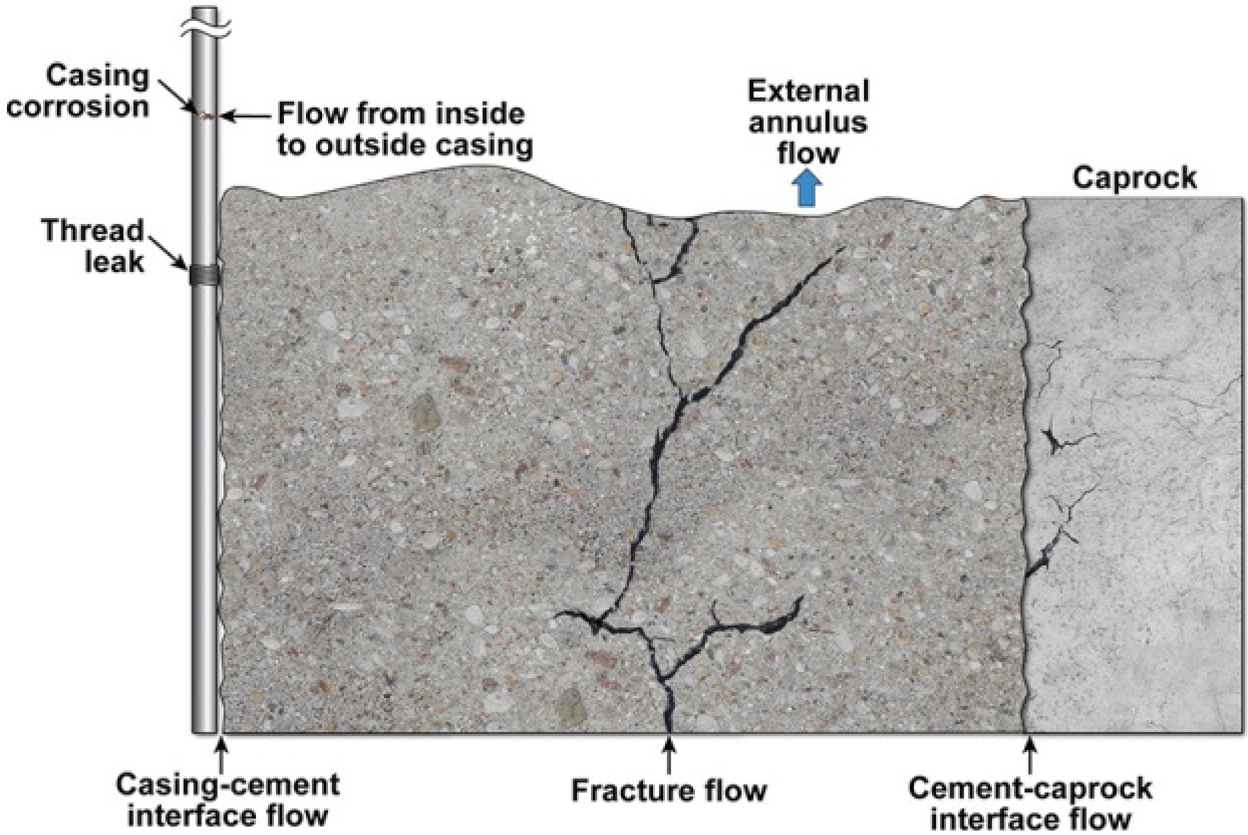

Figure 3. Schematic diagram of CO_2 flow in wellbore, formation rocks and fractures [32].

After CO_2 is injected into the geological storage body, it moves upward and gathers in the lower part of the cap rock under the action of buoyancy. Although the permeability of the caprock is very low, with the increasing CO_2 injection and CO_2 concentration in the formation, CO_2 invades the caprock under the action of concentration gradient and other factors. Furthermore, CO_2 reacts with the caprock chemically, increasing the porosity and permeability of the caprock, destroying its integrity, leading to CO_2 leakage from the caprock (Figure 4) [33].

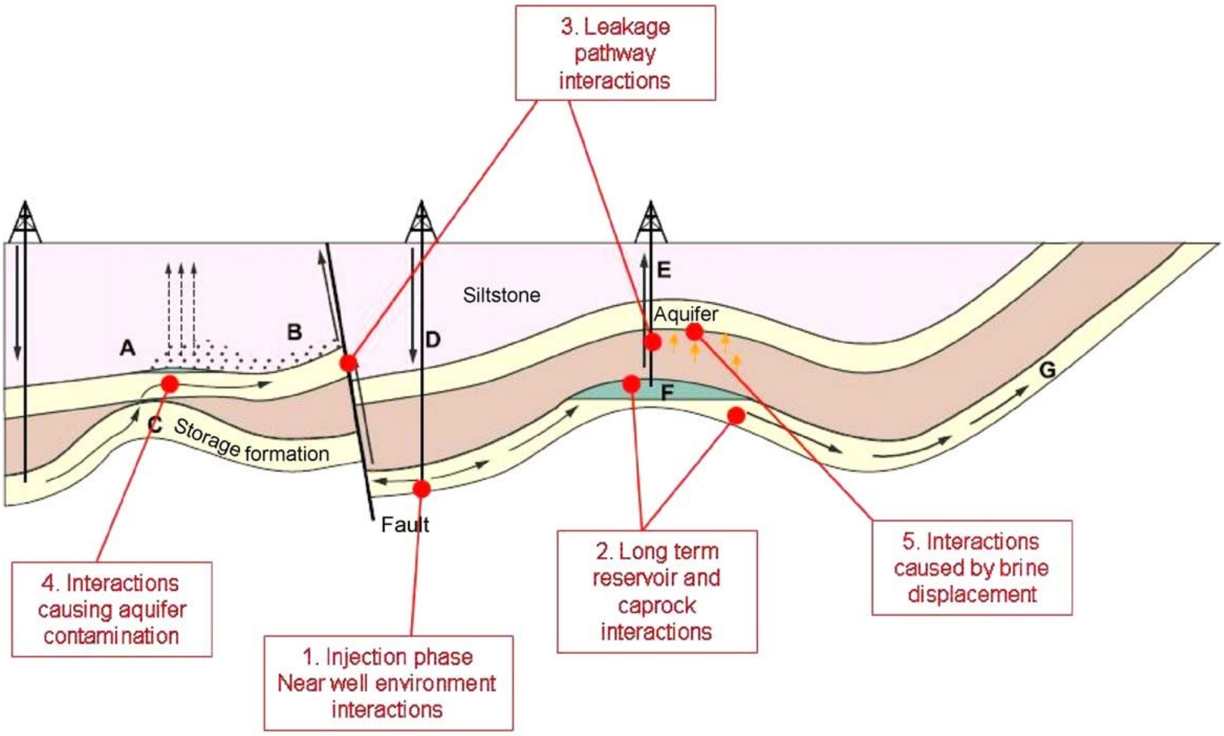

Figure 4. Schematic diagram of a CO_2 injection scheme and identified clusters of CO_2–rock interaction [34]. (Noted: The letters A to G represent CO_2 potential escape mechanisms. A: CO_2 gas pressure exceeds capillary pressure and passes through siltstone; B: Free CO_2 leaks from A into upper aquifer up fault; C: CO_2 escapes through 'gap' in cap rock into higher aquifer; D: Injected CO_2 migrates up dip, increases reservoir pressure and permeability of fault; E: CO_2 escapes via poorly plugged old abandoned well; F: Natural flow dissolves CO_2 at CO_2/water interface and transports it out of closure; G:Dissolved CO_2 escapes to atmosphere or ocean.) 3.2. Risks of CO_2 Storage Leakage.

Among the three leakage paths mentioned in Section 3.1, the leakage process of CO_2 through the faults/fracture system and cap system is slow. Slow leakage can further cause a series of problems such as underground water pollution, soil acidification and ecological destruction. The leakage of CO_2 through the wellbore system is a sudden leakage, which may affect the atmosphere, animals, plants and human health near the leakage area and even threaten their lives [35].

3.1.1. Impact on Underground Water

According to the data of the American "Frio Brine Pioneer Experiment", the injection of CO_2 changes the pH value of underground water from 6 to 3 [36]. The reason is that CO_2 dissolves in water to produce weak acidity, which dissolves reservoir minerals and produces precipitation or new ions. At the same time, the dissolution also leads to cracks in the rock plugging layer, which makes the polluted brine enter the upper groundwater layer, thus, increasing the acidity and hardness of the groundwater. The leaked CO_2 continuously migrates in the underground water and dissolves with the underground water, resulting in certain changes in the groundwater pH value, HCO_3^- concentration, temperature, pressure, conductivity and other parameters, which affects the underground water quality.

3.1.2. Impact on Soil

When the leaked CO_2 reaches the soil through the hydraulic trap, the leaked CO_2 interacts with the water in the soil, which changes the soil properties. The increase in CO_2 concentration not only increases the bacterial content in the soil but also affects the normal growth of crops; however, it has little effect on soil particle size, temperature and pH value [37]. In addition, with the increase in CO_2 concentration, the total amount of metals and ions in the soil is partially affected, and the buried equipment may be corroded [38].

3.1.3. Impact on the Surface Atmosphere

When the leaked CO_2 diffuses into the atmosphere, the absorption of CO_2 to the infrared radiation of the earth and its good thermal insulation will cause the atmospheric temperature to rise, and some changes will take place in the parameters such as air temperature, air pressure and atmospheric humidity, which may lead to significant climate and environmental changes [39]. In addition, because the density of CO_2 is higher than that of air, CO_2 will accumulate in low-lying or poorly ventilated places, which will cause some harm to people, animals and plants.

4. Environmental Monitoring Technology of CO_2 Geological Storage and Leakage

With the large-scale development of CO_2 geological storage projects, the safety and effectiveness of CO_2 storage have attracted more and more attention. The effective implementation of the environmental monitoring of CO_2 storage leakage has become a research hotspot for domestic and foreign scholars. The research has shown that underground monitoring, near-surface monitoring and above-ground monitoring are the core of environmental monitoring of the CO_2 geological storage. A complete monitoring cycle involves four stages: background period, operation period, closing period and after closing period [40]. Among them, underground monitoring is mainly underground water monitoring, near-surface monitoring is mainly soil monitoring and above-ground monitoring is mainly atmospheric monitoring. Underground monitoring methods mainly include infrared gas analysis, vorticity correlation monitoring, LIDAR monitoring and other ground monitoring methods. The near-surface and above-ground monitoring methods mainly include pressure monitoring, electromagnetic performance testing, thermal conductivity testing, geochemical testing, isotope monitoring and so on [41].

4.1. Underground Water Monitoring

The leaked CO_2 migrates in the underground aquifer, and at the same time, it dissolves with the groundwater, which significantly changes the groundwater quality. Therefore, by arranging monitoring points at the CO_2 geological storage site and its surrounding environmental sensitive points and observing the changes in CO_2 concentration, pH value, electrical conductivity, temperature and pressure, as well as HCO_3^-, Ca^{2+} and Mg^{2+} concentrations, we can identify whether the CO_2 leaks or not.

When CO_2 leaks in the underground water, the concentration of CO_2 in the water rises approximately linearly, and the change is the most intuitive and obvious, so the monitoring of CO_2 concentration is taken as the first-class index. When the leaked CO_2 reacts with water to produce carbonic acid, the pH value and conductivity value of water will change, but this change will also be affected by groundwater, underground temperature, pressure and other acidic gases, so the pH value and conductivity value can be used as secondary monitoring indicators. Although the pressure and temperature of groundwater are also affected by CO_2, if the leakage of CO_2 is too small, or the leakage point is far from the monitoring point, it is difficult to observe the change in temperature and pressure, so it is used as a three-level monitoring index. In addition, although the concentrations of HCO_3^-, Ca^{2+} and Mg^{2+} are closely related to CO_2 leakage, due to the limitation of the current technology, the ion concentration monitoring can only be obtained by sampling and inspection, and real-time monitoring cannot be realized. Additionally, the concentrations of Ca^{2+} and Mg^{2+} are reduced to lower concentrations after the concentration peaks, and if the sampling frequency is too small, it leads to misjudgment, so they are used as four-level monitoring indicators. In the actual monitoring process, generally, the primary and secondary indicators are taken as the main monitoring objects, and the secondary and tertiary indicators are taken as the auxiliary evaluation objects.

According to the monitoring principle, the existing underground water monitoring technologies can be divided into indirect monitoring and direct monitoring. Indirect monitoring technology refers to analyzing the leakage of CO_2 in the formation by measuring the changes of relevant parameters in the underground water samples, such as monitoring the concentrations of HCO_3^-, Ca^{2+} and Mg^{2+}. The direct monitoring technology is to directly monitor the underground water through the in-situ monitoring technology, which is the most direct and economical means of monitoring the underground water environment. The monitoring methods of different monitoring indexes and stages of groundwater are shown in the Table 2.

Table 2. Monitoring indexes and methods of groundwater CO_2 leakage [42–46].

Project	**Monitoring Method**		
	Before CO_2 Injection	**During CO_2 Injection**	**After CO_2 Injection**
CO_2 concentration	Sampling	In situ real-time online monitoring of underwater CO_2 concentration monitor	In situ real-time online monitoring of underwater CO_2 concentration monitor
pH	Sampling	In situ real-time online monitoring of groundwater monitor	In situ real-time online monitoring of groundwater monitor
Electrical conductivity	Sampling	In situ real-time online monitoring of groundwater conductivity monitor	In situ real-time online monitoring of groundwater conductivity monitor
Temperature and pressure	In situ real-time online monitoring of groundwater by multi-parameter monitor	In situ real-time online monitoring of groundwater by multi-parameter monitor	In situ real-time on line monitoring of groundwater by multi-parameter monitor
HCO_3^- concentration	Sampling	Sampling	Sampling
Ca^{2+} and Mg^{2+} concentration	Sampling	Sampling	Sampling
Monitoring frequency	Once a month	On-line monitoring once every 15 min; Sampling twice a month.	On-line monitoring once every 15 min; Sampling twice a month.

4.2. Soil Monitoring

The basic principle of soil monitoring of CO_2 storage leakage is the same as that of underground water monitoring; that is, whether CO_2 storage leakage has occurred can be judged by monitoring the changes in indicators related to CO_2 storage leakage in soil. The CO_2 flux, CO_2 concentration, soil moisture content, soil pH value, organic carbon content and soil electrical conductivity all change with the extension of CO_2 storage and leakage time. Among them, CO_2 flux, CO_2 concentration and soil electrical conductivity in soil gradually increase with the extension in CO_2 leakage time, while soil moisture content, pH value and organic carbon content gradually decrease with the increase in time [47]. In addition, each index is affected by CO_2 leakage in different seasons, soil moisture content and temperature.

Among the soil monitoring indicators, CO_2 flux and CO_2 concentration are the most intuitive monitoring indicators. Once the leaked CO_2 breaks through the hydraulic trap and enters the soil, the CO_2 flux and concentration immediately increase, especially in the soil with loose soil and large porosity. Therefore, these two indicators can be used as the first-class monitoring indicators. After the CO_2 leak, CO_2 reacts with soil moisture to produce carbonic acid, which reduces soil moisture content and pH value. This leads to the change in soil moisture content and pH value. As the change in soil moisture content is also affected by the monitoring season and climate, the appropriate time for monitoring moisture content and pH value can be selected according to the local temperature and rainfall change law. The relevant research shows that with the increase in soil temperature, the decomposition rate of organic carbon is accelerated, and the content of organic carbon is continuously reduced. The decrease in organic carbon content in soil in summer and autumn is greater than that in other seasons, and after CO_2 leakage, the decrease rate of organic carbon is faster and the trend is more obvious. Therefore, the content of organic carbon can be regarded as the key monitoring index in summer and autumn. In conclusion, we can use soil moisture content, pH value and organic carbon content as secondary monitoring indicators; In addition, although soil conductivity, total bacteria and metal ions can also reflect the leakage of CO_2 to some extent, they all need certain preconditions, so they can be used as three-level monitoring indicators. See Table 3 for monitoring methods and technical characteristics of each index.

Table 3. Main environment indicators and monitoring methods for CO_2 leakage in soil [48–51].

Soil Environmental Index	Monitoring Methods	Applied Range
Soil CO_2 flux	Accumulation chamber method	The accumulation chamber with an open bottom is placed in the soil, and the variation of CO_2 flow through the soil is calculated based on the change rate of CO_2 concentration, which can quickly and effectively determine the CO_2 flow in a specific area but can only provide real-time data in a limited area.
Soil CO_2 concentration	Non-dispersive infrared gas analysis (IRGA)	The soil CO_2 concentration is monitored intermittently or continuously, which is convenient to measure and can accurately, quickly and stably reflect CO_2 leakage, but it is difficult to determine CO_2 leakage rate and total leakage amount.
Soil conductivity	(1) Electrode method (2) Sampling method:	(1) The electrode method is mainly used, and the conductivity meter is used to directly measure the soil moisture content. (2) The soil samples are measured in the laboratory, and the results are as follows. The results are more accurate, but in situ monitoring is impossible.
Soil moisture content	(1) Positioning method (2) Remote sensing method	(1) It mainly includes the capacitance method, time domain reflection method (TDR), frequency domain reflection method (FDR), etc. It has high precision and can be used for in situ measurement, but the cost is high; (2) The remote sensing method has good penetrability and is suitable for large-scale monitoring, but it is greatly affected by surface parameters and has high cost.
Soil pH value	Main electrode method	This method is used to determine the hydrogen ion concentration in the sample by pH meter. In addition, the utilized methods are the mixed indicator colorimetry, pH test paper method, visible light spectrum extraction method, sensor monitoring method, etc.
Soil organic carbon content	Infrared method, titration method, spectrophotometry and other methods.	The collected soil gas was measured in the laboratory by non-dispersive methods.

4.3. Atmospheric Monitoring

Because the atmosphere itself contains a high concentration of CO_2 (approximately 340 ± 40 ppm), the micro or small amount of CO_2 (about 10~100 ppm) leaked from the carbon storage project may often be submerged in the fluctuation of the background concentration, so it is particularly difficult to monitor and identify CO_2 leaked into the surface atmosphere. The main means of atmospheric monitoring in the process of CO_2 storage are infrared gas monitoring, atmospheric CO_2 flux monitoring and atmospheric CO_2 tracer monitoring [5]. These three technical means are common technical methods of storage monitoring projects that are widely used in the world.

The research into infrared gas monitoring technology is based on the characteristics of the CO_2 near-infrared absorption spectrum, mainly including IRGA (infrared gas analyzer) and LOIR (long-range open path infrared detection and modulated laser) [52,53]. Among them, the IRGA method can realize point monitoring, with high monitoring accuracy and quick response, but it is difficult to carry out regional measurements. Although the LOIR method can realize regional monitoring, it is not mature at present and needs further research and development. The monitoring of the atmospheric CO_2 flux is mainly realized by the eddy covariance (EC) method, which has the advantages of a wide monitoring range and little influence from the surrounding environment but also has the disadvantages of long-term monitoring to obtain key parameters such as leakage [54]. The atmospheric CO_2 tracer monitoring is to add a tracer to the storage CO_2 and realize the leakage monitoring of CO_2 storage by monitoring the tracer concentration [55]. Although this technology has high sensitivity, it also has some problems, such as high cost and the difficulty in selecting a tracer.

5. Technical Development Suggestions

5.1. Current Situation of CCUS Technology in China

According to "China's Annual Report on CO_2 Capture, Utilization and Storage (CCUS) (2021)" [12], there are currently approximately 40 CCUS demonstration projects in operation and under construction in China that are distributed in 19 provinces. At present, fewer than 10 years remain before China will achieve the goal of peak CO_2 emissions, and fewer than 40 years from peak CO_2 emissions to achievingthe goal of carbon neutrality. From the demand of carbon-neutral emission reduction, according to the current technology development forecast, the emission reduction required by CCUS technology in 2050 and 2060 will be 60~14 billion tons and 1~18 billion tons of CO_2 respectively. In 2060, biomass carbon capture and s torage (BECCS) and direct air carbon capture and storage (DACCS) need to reduce CO_2 emissions by 300–600 million tons and 200–300 million tons, respectively [12]. At present, under the situation that China's coal-based energy consumption structure is difficult to change in a short time, it is an effective measure to implement CO_2 geological storage to realize China's carbon emission reduction commitment.

In recent years, the geological storage of CO_2 in China has developed rapidly in the fields of regional investigation and evaluation, key technology research and engineering demonstration, but there is still a big difference compared with foreign countries. According to the main CCUS project process in China (Table 4), CO_2 is mostly stored by CO_2-EOR, which has good economic benefits [56–60]. This technology has entered the commercial application level in the world, but it is still in the industrial demonstration stage in China. There is a big difference between China and the world. On 6 August 2012, in terms of saline aquifer storage, the first full-process demonstration project of CO_2 storage in underground saline aquifers in China was completed and put into operation [61]. This demonstration project is a key project supported by the China National Science and Technology Support Plan. The success of the project also indicates that the deep saline aquifer storage technology in China has developed from the conceptual stage to the industrial demonstration stage. As for the storage in coal seams, China is still in the stage of exploration and demonstration. In 2004, China carried out the CO_2-ECBM pilot experiment in the south of Qinshui Basin, and the production of the single well increased obviously [62]. In 2011–2012, China United Coalbed Methane Co., Ltd. cooperated with the Commonwealth Scientific and Industrial Research Organization of Australia (CSIRO) to carry out an intermittent single-well injection-production test in a coal seam (depth of 560 m) in Liulin, Shanxi Province for approximately 8 months. A total of 460 t CO_2 was injected into this project, and the tracing method was used to monitor CO_2 migration [63]. In 2013–2015, the injection test was carried out again in the Qinshui Basin [64]. By capturing CO_2 from coal-fired power plants, a 4491 t CO_2 injection was injected into a 900 m deep coal seam [65].

Table 4. Major CCUS full-process projects in China [66].

No.	Project	Running State	Startup Year	Emission Source	Capture Technique	Transport Method	Storage and Utilization Mode	Production Capacity (10,000 Tons/Year)
1	CO_2-EOR Project of Zhongyuan Oilfield, Sinopec	running	2006	ammonia tail gas from chemical fertilizer plant	before burning	tanker	EOR	12
2	CO_2-EOR Project of Jilin Oilfield, PetroChina	running	2007	natural gas purification	before burning	tube	EOR	35~60
3	CCUS Project of Shengli Oilfield, Sinopec	running	2010	coal-fired power station	after burning	tanker	EOR	4
4	CO_2-ECBM Project of China United Coalbed Methane Co., Ltd.	running	2010	purchased gas	-	tanker	ECBM	0.1~0.2
5	CCS Demonstration Project of China Shenhua Energy Co., Ltd.	completed	2012	coal to oil	before burning	tanker	saline aquifer storage	10
6	CO_2 capture and CO2-EOR Demonstration Project of Yanchang Petroleum	running	2013	coal chemical industry	before burning	tanker	EOR	5
7	EOR Project of Daqing oil field, PetroChina	running	2014	natural gas purification	before burning	tanker + tube	EOR	20
8	CCUS Demonstration Project of GreenGen.Co., Huaneng Group	building	2015	coal-fired power station	before burning	tanker	EOR and saline aquifer storage	10
9	CCUS-EOR Project of Karamay Dunhua Petroleum	running	2017	methanol plant	before burning	tanker	EOR	10
10	EOR Project of Changqing Oilfield, PetroChina	running	2017	methanol plant	after burning	tanker	EOR	5~10
11	Full-process CCS Demonstration Project of Guohua Electrical Power Corporation	building	2019	coal-fired power station	after burning	-	-	15
12	Carbon Capture and Comprehensive Utilization Project of Guoneng Taizhou Company	building	2020	coal-fired power station	-	-	EOR	50
13	Offshore CCUS Project in South China Sea of Cnooc	running	2021	natural gas purification	-	-	saline aquifer in seabed	30
14	EOR Project of Qilu Petrochemical-Shengli Oilfield, Sinopec	running	2021	chemical plant	-	-	EOR	71~100
15	Full-process Demonstration Project of CCUS in East China Petroleum Bureau, Sinopec	building	2021	chemical plant	before burning	tanker + ship	EOR	50~100

5.2. Development Suggestions

At present, although CCUS technology in China has gradually become a system project, it is still in the demonstration research stage on the whole. Some problems, such as unclear CO_2 storage mechanism and main control factors, imperfect CO_2 storage risk assessment, incomplete monitoring technology system for the whole life cycle of CO_2 storage and irregular CO_2 storage risk response and emergency treatment, have seriously hindered the development, popularization and application of this technology. Aiming at the above problems of CO_2 storage technology in China, the following technical development suggestions are put forward.

5.2.1. Strengthening the Research on CO_2 Storage Mechanism and Main Control Factors

A clear CO_2 storage mechanism is the basis for achieving safe and efficient CO_2 storage. However, the geological storage of CO_2 is often a complex relationship among CO_2–rock–fluid, which interact and influence each other to determine the safety state of this system [67]. The multi-field coupling mechanism in the process of carbon storage is an urgent problem to be solved. Therefore, we should comprehensively use multi-disciplinary knowledge such as fluid mechanics, physical chemistry, rock mechanics, etc., and use numerical simulation, similarity simulation and other means to study the change law of the CO_2–rock–fluid system and the damage mechanism of geological bodies during CO_2 sequestration. At the same time, the influence and mechanism of geological features, storage environment, storage conditions and other factors on CO_2 safe storage should be analyzed. On the basis of the above research, the CO_2 sequestration mechanism and main control factors are obtained.

5.2.2. Improving the Risk Assessment Method of CO_2 Storage

When choosing the CO_2 storage area, we should consider not only the storage potential but also the economy and safety of storage. There are many studies on the evaluation of storage potential at home and abroad but few on the evaluation of storage safety [68,69]. To solve this problem, we can use the techniques of ground penetrating radar (GPR), 3D fault scanning, electrical prospecting, etc., to carry out multi-scale and all-round geological structure observation and establish relevant visual models. This model can realize the tracking, detection and evaluation of the structural stability of geological bodies. On this basis, considering the multi-field coupling effect that CO_2 sequestration may bring, a comprehensive technical index system of carbon sequestration risk detection will be constructed, and a complete set of the technical methods of risk detection and safety assessment will be formed.

5.2.3. Building a Monitoring Technology System for the Whole Life Cycle of CO_2 Storage

Most of the existing CO_2 storage leakage monitoring technologies focus on CO_2 leakage monitoring, but CO_2 leakage obviously lags behind the structural damage and instability of the sealed geological body. That is, when CO_2 storage leakage is detected, the structure of the sealed geological body is damaged [70]. To realize the safety monitoring of CO_2 storage, it is necessary to carry out the whole-cycle monitoring of CO_2 storage. In the early stage of CO_2 storage, through tracer monitoring or numerical simulation, research on CO_2 migration direction is required; In the middle and late stage of CO_2 storage, three-dimensional environmental monitoring will be continuously carried out to realize real-time continuous monitoring of CO_2 storage leakage; After the end of CO_2 storage, combined with CO_2 storage mechanism and migration law, the key environmental indicators should be monitored regularly to ensure the effectiveness of CO_2 storage.

5.2.4. Standardizing CO_2 Storage and Leakage Risk Response System

While monitoring the leakage of CO_2 sequestration, corresponding prevention and control measures and emergency treatment should also be provided. To build an emergency system, we can first simulate the risk and degree of multi-field coupling, geological structure, fault slip, engineering disturbance, earthquake and other disturbances to the structural stability of the storage site under the consideration of various risk factors that would lead to the structural instability of geological bodies and CO_2 leakage. On this basis, we can study the disaster occurrence process, damage degree and the influence degree of CO_2 migration characteristics on geological bodies. Then, according to the research results, the corresponding emergency measures are put forward, and their feasibility is analyzed and verified. Finally, based on risk analysis and emergency treatment methods, the corresponding standards are constructed so as to standardize the emergency treatment of CO_2 sequestration and leakage.

6. Conclusions

According to the types and mechanisms of CO_2 geological storage, the ways and hazards of CO_2 geological storage leakage, and the existing environmental monitoring technologies of CO_2 storage leakage and combined with the development status of CCUS technology in China, we put forward the next development suggestions for China's environmental monitoring technologies of CO_2 storage leakage under the background of "double carbon" and provide decision support for the realization of the "double carbon" strategic goal. The main conclusions are as follows:

(1) The geological storage types of CO_2 mainly include depleted oil and gas reservoirs, deep saline aquifers and deep unmanageable coal seams, and the main storage mechanisms include physical storage mechanisms, chemical storage mechanisms and adsorption mechanisms, such as structural geological storage, binding storage, hydrodynamic storage, dissolution and storage and so on.
(2) There are three leakage ways in CO_2 storage: along the wellbore system, fault/fracture system and caprock system. Once CO_2 leaks, it has a certain impact on underground water, soil and atmosphere.
(3) The monitoring of groundwater, soil and atmosphere is the core of the environmental monitoring technology of CO_2 geological storage and leakage.
(4) The safe and efficient geological storage of CO_2 is the key to achieve the "double carbon" goal in China. In the future, China can promote the progress of CO_2 geological storage monitoring technology and help achieve the goal of "double carbon" by strengthening the research on CO_2 storage mechanism and main control factors, perfecting the risk assessment method for CO_2 storage, constructing the monitoring technology system for the CO_2 storage life cycle, and standardizing the CO_2 storage risk response system.

Author Contributions: Conceptualization, Y.C. and J.B.; methodology, Y.C. and J.B.; investigation, Y.C. and J.B.; resources, S.L., S.C. and F.L.; writing—original draft preparation, Y.C.; writing—review and editing, S.L., S.C. and F.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Fourth Batch of Leading Innovative Talent's Introduction and Cultivation Projects of Changzhou (grant number CQ20210109).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be provided if anyone needs it.

Acknowledgments: The authors would like to acknowledge the support provided by Analysis and Testing Center, NERC Biomass of Changzhou University.

Conflicts of Interest: The authors declare no conflict of interest.

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