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# Plant communities and potential phytoremediation species for resource utilization of abandoned drilling mud

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Oil and gas development produces a large amount of abandoned drilling mud, which may be a source of pollution but may also be a potential resource. A quadrat sampling method was used in the Changqing Oilfield to investigate the plant community characteristics inside and outside abandoned drilling mud pits at different completion times. The importance value of plant showed that the natural succession of plant communities in the abandoned drilling mud pool could be divided into three stages: (1) 4–8 years after the completion of the well, *Leymus secalinus, Calamagrostis epigeios* with the importance values of more than 100, were dominant species in the initial construction stage; (2) 9–13 years after the succession, the intense competition stage of the plant community, although the importance value of plant inside the mud pit had decreased, it was still higher than the importance value of plant outside the mud pool. The importance values of *L. secalinus* and *Artemisia scoparia* outside the mud pool were 62.5 and 52.5, while those in the mud pool were 95 and 75, respectively; (3) 23–28 years after the succession, the gradual stabilization stage of the plant community, the importance value of plant was lower than that in the mud pool. *Leymus secalinus*, *C. epigeios* and *A. scoparia* could be used for phytoremediation of abandoned drilling soil for their higher importance values. Changes of Shannon–Wiener index, Pielou index, Community ecological dominance and vegetation biomass showed that the mud pit was suitable for the recovery and growth of the dominant species, improved the diversity of plant communities inside the mud pit compared with the stable plant community outside the mud pit. Abandoned drilling mud increased the content of nitrogen, potassium and trace elements in plants. While the variation coefficient of heavy metal content in plants inside and outside the mud pit was large, but the content of heavy metals in plants was within the normal range. Abandoned drilling mud has the potential for resource utilization on the premise of ensuring soil quality and safety. This study provides information on the comprehensive treatment, resource utilization, disposal economics and environmental safety of abandoned drilling mud.

KEYWORDS

**abandoned drilling mud, plant community, potential phytoremediation species, resource utilization, vegetation restoration**

# 1 Introduction

Oil is the "blood" of modern industry and an indispensable strategic resource for a country's survival and development. As one of the three major oil fields in China, the Changqing Oilfield has a total oil resource of about 8.6 billion tons and a total natural gas resource of about 11 trillion cubic meters (Wang M. J. et al., 2021; Wang Z. et al., 2021; Wei et al., 2021). However, a large amount of abandoned drilling mud produced by drilling operations in oil and gas development is discharged to the ground, causing environmental pollution and regional ecological environment damage (Wang M. J. et al., 2021). Chakravarty et al. (2022) found that the elevated levels of polycyclic aromatic hydrocarbons (PAHs) and its allied threat to living organisms caused alteration in biological conditions of the soil, made soil unfit for vegetation. Borah and Deka (2023) found that crude oil-associated heavy metals (HMs) had inhibitory effects on soil enzyme activities, and it also had negative effect on the bacterial diversity and activity of the soil bacterial community, thus hampered the ecosystem processes. Singha et al. (2022) also found the same conclusions that the spent oil contamination had caused a significant reduction in urease, dehydrogenase, amylase, catalase and alkaline phosphatase enzyme activities and total bacterial population in the soil. The comprehensive treatment of drilling mud has become an urgent problem to be solved in the protection of the environment in the oilfield development areas (Al-Ateeqi et al., 2022). Furthermore, in the context of increasingly tense cultivated land resources, it is also necessary to reuse abandoned drilling land, which has become a relevant topic in global land rehabilitation and soil remediation research (Zvomuya et al., 2008; Ali et al., 2013; Hu et al., 2014; Wang Z. et al., 2021; Xiao and Wu, 2021; Borah and Deka, 2023).

The exploitation area of the Changqing Oilfield is a typical fragile ecological environment area (Wei et al., 2021). The exploitation activities have changed the original vegetation cover of the land, resulting in the loss of biodiversity, water and soil, as well as land desertification (Zhu et al., 2018). Use of local material may be an excellent measure to promote soil improvements and ecological rehabilitation. Water-based drilling mud (WBM), widely applied in the drilling process of the Changqing Oilfield, compared to other nonaqueous, it was found to be more environmental-friendly (Fu et al., 2022). Meanwhile, the water-based spent drilling mud (WBSM) has been an essential by-product in the oil and gas industry for several decades, it is a potential nutrient pool that contains many nutrients and soil organic matter (Fink and Drohan, 2015; Fu et al., 2022). Previous researchers have carried out research on the soiling of abandoned drilling mud from different angles and have analyzed the feasibility of converting abandoned drilling mud into soil resources (Alahabadi et al., 2017; Fu et al., 2022). Fu et al. (2022) found that drilling mud altered the texture of loessial soil and increased soil total porosity and changed pore size distribution. Whether the abandoned drilling mud can be used to accelerate the restoration of the ecological environment of the well requires an investigation of the ecological restoration of the existing abandoned mud landfill treatment well. Theoretically, the natural recovery vegetation is more stable than the artificial plant community, but the natural recovery rate of vegetation is slow. Understanding the natural recovery process of vegetation in the existing abandoned mud landfill treatment well has a strong reference value for the rational use of abandoned drilling mud to build artificial plant communities and realize the rapid recovery of the ecological environment in the well. At present, there is a lack of research on vegetation restoration under the *in situ* treatment of abandoned drilling mud. Based on this, this paper used the research method of space instead of time to complete the research.

Bioremediation is an effective and irreplaceable method for soil remediation, especially phytoremediation (Rufus et al., 1997; Yoon et al., 2006; Li et al., 2016; Liu et al., 2020; Li et al., 2020; Esposito, 2023; Zha et al., 2023). Phytoremediation is low cost, simple and effective, and will not cause secondary pollution. It causes less disturbance to the environment, while improving the ecological environment and providing economic benefits (Rufus et al., 1997). Most of the existing research has used designated plants or plants that grow well in a certain period to conduct pot experiments, set different oil pollution levels, and compare and screen results according to the performance of different plants (Zhang et al., 2013; Qi et al., 2014; Che et al., 2020; Wang M. J. et al., 2021; Kalita et al., 2022; Leonid et al., 2023). Kalita et al. (2022) studied that *Leucas aspera* treated contaminated soil showed the biochemical enhancement defense of various soil enzyme activities, and signifcant variations in leaf area index, chlorophyll, and biomass contents, it had phytoremediation potential in crude oil polluted soil. Blanco-Velázquez et al. (2000) also proposed that a proper selection of native plant species could play a remarkable role in eliminating petroleum contaminated soil. Al-Thani and Yasseen (2020) studied that a native desert plant *Sporobolus ioclados* might be a promising phytoremediator in Qatar for the contaminated desert soil. Al-Ateeqi (2010), Al-Shehabi and Murphy (2017), Halwagy et al. (1982) found that *Cyperus conglomeratus*, *Haloxylon salicornicum* and *Rhanterium epapposum* could thrive in oil-polluted soils in Kuwait. The present study analyzed the natural succession process of plant communities in and outside the mud pit at different completion times. The selection of remediation plants for abandoned drilling soil is carried out according to the natural succession results of plant communities. The research results can provide a new perspective for the phytoremediation of oil-contaminated soil.

The main purpose of this study was to determine the natural recovery of plant communities under the *in situ* treatment of abandoned drilling mud, select the remediation plants for abandoned drilling mud soil according to the recovery results, and evaluate the impact of abandoned drilling mud on plant nutrients and pollution. This study leads to better understanding of the evolution of local plant species under the *in situ* treatment of abandoned drilling mud, and also provides a low-cost and eco-friendly option for the *in situ* treatment of abandoned drilling mud. The research results can provide a reference for the resource utilization and ecological restoration of abandoned drilling in similar ecologically fragile areas.

# 2 Materials and methods

## 2.1 Overview of the study area

The oil and gas development zone of the Changqing Oilfield is located in the Ordos Basin, spanning Shaanxi, Gansu, Ningxia, Inner Mongolia and Shanxi in China. It has rich oil and gas reserves and has become the largest oil and gas field production base in China. This area is a typical fragile ecological environment area, with serious wind and water erosion, low precipitation, and widely

**TABLE 1** Information of sample point.

| Order number | Well number | Completion time (year) | Order number | Well number | Completion time (year) |
|---|---|---|---|---|---|
| 1 | Sudong56-04# | 2014 | 8 | Su14-11-37# | 2008 |
| 2 | Shan377# | 2013 | 9 | Su14-11-38# | 2007 |
| 3 | Tao2-1-25# | 2012 | 10 | Wu17-6# | 2002 |
| 4 | G37-12# | 2011 | 11 | Wu19-8# | 2002 |
| 5 | Shan262# | 2010 | 12 | G41-9# | 2000 |
| 6 | Shan246# | 2010 | 13 | G-42-8# | 2000 |
| 7 | Tao2-8-8# | 2008 | 14 | Shan67# | 1992 |

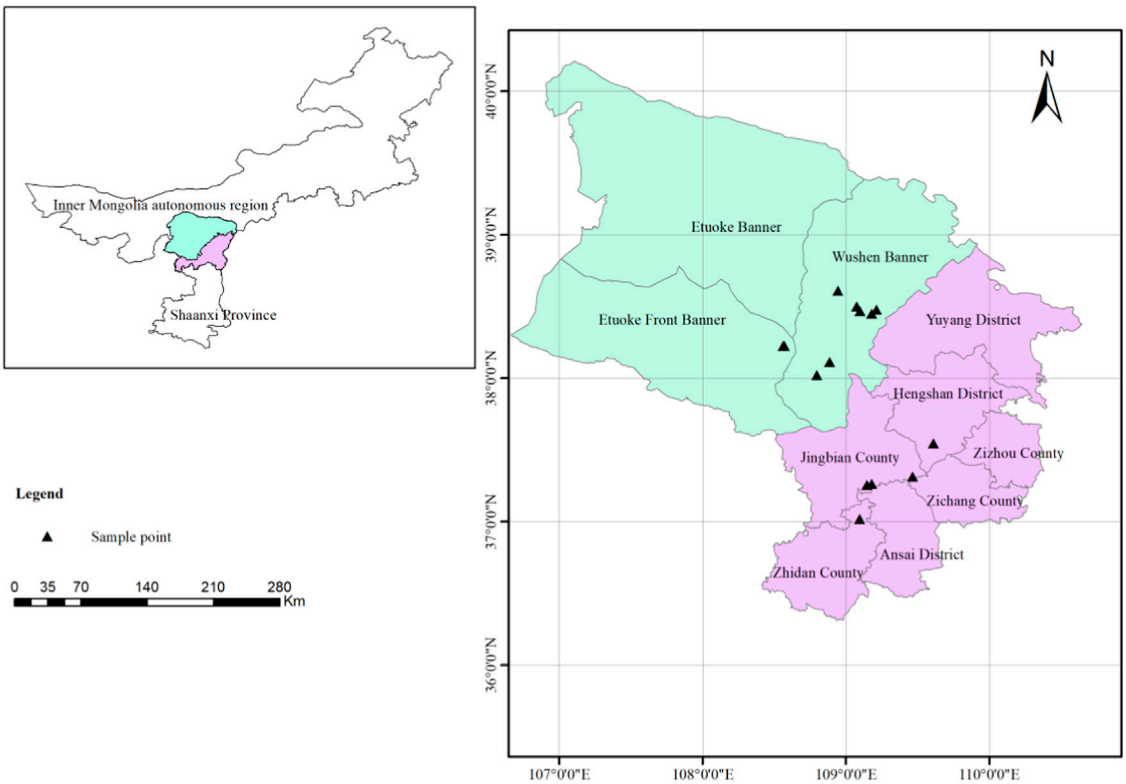


FIGURE 1
Study area and sample point.

distributed saline soil. The climate is a warm temperate semi-arid continental monsoon climate. The average annual temperature is 10°C, and the soil is mainly yellow and sandy soil, which is loose. The water-based drilling fluid system is widely used in the drilling process of the Changqing Oilfield. Its composition is simple, non-toxic, harmless, and partially biodegradable.

## 2.2 Sample collection

The field sampling was conducted in October 2018. The 14 wells involved in sampling are shown in Table 1 and Figure 1. According to the quadrat sampling method, a sample of 1 m × 1 m was randomly arranged, repeated 3 times, the plant conditions inside and outside the mud pit of the well with different completion years were investigated. The sample plots outside the mud pit around the well were selected as the control. We recorded the species, plant height, coverage, frequency and biomass of plants in the quadrat ($n$ = 84 samples). All living plants in the sample were sorted into species. The nomenclature of plant species and confirmation used the Subject Database of China Plant (www.plant.nsdc.cn) and the World Flora online (www.worldfloraonline.org). All species were dried indoors (70°C to constant weight) in each sample to obtain the aboveground biomass of the vegetation. We selected *Artemisia scoparia* as the representative plant to measure the nutrient and heavy metal content of the plant inside and outside the mud pool.

## 2.3 Research methods

(1) The importance value of species in the plant community = 1/3 [coverage + height + frequency].
(2) Determination of species diversity

Shannon–Wiener index (H) and Pielou index (E) were selected for the analysis of species diversity characteristics.

1) Shannon–Wiener Index

$$H = -\sum_{i=1}^{s} P_i \ln P_i \quad (1)$$

Here, $H$ is the diversity index, $P_i$ is the ratio of the importance value of the $i$ plant species to the sum of the importance value of all plant species, and $S$ is the number of species in the plant community.

2) Pielou index:

$$E = H/LnK \quad (2)$$

Here, $E$ is the evenness index, $H$ is the diversity index, and $K$ is the number of species in the plant community.

(3) Community ecological dominance:

$$C = \sum_{i=1}^{s} \left(\frac{m_i}{M}\right)^2 \quad (3)$$

Here, $C$ is the ecological dominance, $M$ is the sum of the importance values of all species in the plant community, and $m_i$ is the importance value of the $i$ plant species.

## 2.4 Analysis of plant samples

The plant sample was washed with tap water to remove the dust and dirt attached to the surface, and then was washed with deionized water, dried in the air, and dried in the oven to constant weight; its biomass was measured.

As the representative plant, *A. scoparia* was ground and sieved (100 mesh). One Gram of sample was digested with 6 mL of concentrated $HNO_3$ and 2 mL of concentrated $H_2O_2$ in a microwave digestion instrument (MDS-6G, Shanghai Xinyi Microwave Chemical Technology Co., Ltd., Shanghai, China), till a clear solution was obtained. The digested sample was allowed to cool down. Upon cooling, the volume of the solution was maintained to 50 mL with double deionized water and fltered using Whatman paper no. 1. A blank digest was carried out in the same way. N of the digested plant samples was measured following Kjeldahl method by automatic nitrogen meter (K1100, Haineng Future Technology Group Co., Ltd., Shandong, China), P by spectrophotometry following Molybdenum antimony colorimetric method (Cintra 2020; GBC Corporation, Melbourne, Australia), K by flame atomic absorption spectrophotometry and trace elements (Zn, Mn, Cu, Fe) and heavy metals (Cd, Cr, As, Pb) by ICP-OES (Agilent 5800 ICP-OES, Agilent Technologies, Santa Clara, United States) according to Tuzen et al. (2007), Sharma and Bhardwaj (2007).

## 2.5 Quality control

All laboratory glassware for analysis was presoaked in 50 mg $L^{-1}$ detergent solution for no less than 8 h and washed using tap water, then soaked in 150 mL $L^{-1}$ 14% (v/v) $HNO_3$ solution overnight and rinsed using deionized water before use. Reagents used in this study were of analytical grade. The quality assurance adopts the double parallel sample and standard recovery method. The recovery rate of each element was 93.12%–96.21%, which conformed to the quality control standard of element analysis.

## 2.6 Statistical analysis

Statistical analyses were performed using the SPSS software package (version 26.0) (Statistical Graphics Corp., Princeton, United States). Means and standard deviations were calculated for three replicates. Means were compared by Duncan's multiple range test at a significance level of 0.05. The coefficient of variation was calculated as: CV = (standard deviation/mean)×100.

# 3 Results

## 3.1 Natural recovery process of vegetation under *in situ* treatment of abandoned drilling mud

Comparing the natural succession and change of vegetation inside and outside the mud pit (Table 2), the natural recovery of plant communities in the mud pit could be divided into three stages:

1) The initial construction stage of dominant species. Approximately 4–8 years after the completion of the well (2010-2014), the dominant species of each plant community were mainly *Leymus secalinus, Calamagrostis epigeios* and *Phragmites australis*, with the importance values of more than 100, representing suitable plants in the mud pool environment at the early stage of well completion. *Calamagrostis epigeios* was an important companion species. The species and number of plant communities in each well were different; some were relatively rich, such as G37-12# and Shaan262#, and some were dominated by single species, such as Shaan377, indicating that the plant community was unstable at the early stage of well completion.

At this time, the dominant species in the plant communities outside the mud pool were *L. secalinus, C. epigeios* and *Artemisia desertorum*, with the importance values of about 50. Compared with those in the mud pool, not only were the dominant species different, but the importance values were also very different. The companion species outside the mud pit which was a stable plant community were more abundant than those inside the mud pit. Through comparison, it could also be found that the plant community in the mud pit was unstable at the initial stage of well completion.

2) The stage of intense community competition. After the natural restoration of vegetation over 10–11 years (completion of the

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**TABLE 2 Changes of importance values of species inside and outside mud pit at different completion time.**

| Completion time (year) | Inside the mud pit | | Outside the mud pit | |
|---|---|---|---|---|
| | Species composition | Importance value | Species composition | Importance value |
| 2014 | *Phragmites australis* | 50.5 b | *Calamagrostis epigeios* | 52.5 a |
| | *Artemisia desertorum* | 50 b | *Artemisia scoparia* | 40 c |
| | *Lespedeza daurica* | 3 i | *Artemisia argyi* | 36.5 d |
| | *Sconchus oleraceus* | 6 h | *Phragmites australis* | 31 e |
| | *Convolvulus arvensis* | 8 g | *Heteropappus hispidus* | 16.5 f |
| 2013 | *Calamagrostis epigeios* | 110 a | *Calamagrostis epigeios* | 58.5 b |
| | | | *Lespedeza davurica* | 22.5 c |
| | | | *Artemisia scoparia* | 16.5 d |
| 2012 | *Artemisia scoparia* | 67.5 a | *Artemisia desertorum* | 55 b |
| | *Sconchus oleraceus* | 5.5 f | *Artemisia scoparia* | 40 c |
| | | | *Lespedeza davurica* | 28 d |
| | | | *Heteropappus hispidus* | 15.5 e |
| | | | *Sconchus oleraceus* | 4 f |
| 2011 | *Leymus secalinus* | 50 b | *Leymus secalinus* | 56.5 a |
| | *Artemisia scoparia* | 39 c | *Artemisia scoparia* | 18 d |
| | *Lespedeza davurica* | 18 d | *Oxytropis racemosa* | 10.5 e |
| | *Euphorbia humifusa* | 3.5 h | *Heteropappus altaicus* | 10 e |
| | *Heteropappus altaicus* | 8 f | *Lespedeza davurica* | 5.5 g |
| | *Gueldenstaedtia stenophylla* | 3 h | *Euphorbia humifusa* | 3 h |
| 2010 | *Leymus secalinus* | 102 a | *Artemisia desertorum* | 43 b |
| | *Artemisia scoparia* | 29.5 c | *Setaria viridis* | 18 e |
| | *Lespedeza davurica* | 22 d | *Artemisia lavandulifolia* | 11.5 g |
| | *Artemisia lavandulifolia* | 18 e | | |
| | *Plantago asiatica* | 13 f | | |
| | *Heteropappus hispidus* | 1.5 h | | |
| 2010 | *Phragmites australis* | 105 a | *Leymus secalinus* | 82.5 b |
| | *Astragalus adsurgens* | 63 c | *Lespedeza davurica* | 45 d |
| | *Heteropappus hispidus* | 20.5 f | *Artemisia scoparia* | 29 e |
| | | | *Rudbeckia laciniata* | 4 g |
| | | | *Stenosolenium saxatile* | 3 gh |
| | | | *Conyza japonica* | 2 h |
| 2008 | *Poa annua* | 55 a | *Artemisia scoparia* | 25 b |
| | *Artemisia scoparia* | 20 c | *Heteropappus hispidus* | 15 d |
| | *Setaria viridis* | 20 c | *Lespedeza davurica* | 5 h |
| | *Convolvulus arvensis* | 11 e | | |
| | *Heteropappus hispidus* | 10 f | | |
| | *Sconchus oleraceus* | 8.5 g | | |

(Continued on following page)

TABLE 2 (*Continued*) Changes of importance values of species inside and outside mud pit at different completion time.

| Completion time (year) | Inside the mud pit | | Outside the mud pit | |
|---|---|---|---|---|
| | Species composition | Importance value | Species composition | Importance value |
| 2008 | *Artemisia scoparia* | 60 b | *Artemisia lavandulifolia* | 66.5 a |
| | *Calamagrostis epigeios* | 50.5 c | *Calamagrostis epigeios* | 32.5 d |
| | *Leymus secalinus* | 13.5 e | *Artemisia scoparia* | 5 g |
| | *Lespedeza davurica* | 7.5 f | | |
| | *Artemisia lavandulifolia* | 3.5 h | | |
| 2007 | *Artemisia scoparia* | 60 a | *Artemisia scoparia* | 30 b |
| | *Calamagrostis epigeios* | 25 c | *Phragmites australis* | 9 e |
| | *Artemisia lavandulifolia* | 23 d | *Lespedeza davurica* | 5 f |
| | | | *Elymus dahuricus* | 3 g |
| 2002 | *Artemisia scoparia* | 58 b | *Artemisia scoparia* | 62.5 a |
| | *Leymus secalinus* | 10 e | *Lespedeza davurica* | 22 c |
| | *Lespedeza davurica* | 9.5 e | *Setaria viridis* | 16.5 d |
| | *Artemisia argyi* | 5 g | *Plantago asiatica* | 7.5 f |
| | | | *Sconchus oleraceus* | 4.5 g |
| 2002 | *Artemisia scoparia* | 75 a | *Artemisia scoparia* | 60.5 b |
| | *Leymus secalinus* | 21 c | *Leymus secalinus* | 13 e |
| | *Phragmites australis* | 19.5 d | *Lespedeza davurica* | 8 f |
| | *Lespedeza davurica* | 4.5 g | | |
| 2000 | *Leymus secalinus* | 95 a | *Leymus secalinus* | 57.5 b |
| | | | *Artemisia scoparia* | 52.5 c |
| | | | *Lespedeza davurica* | 5 d |
| | | | *Heteropappus hispidus* | 3 e |
| 2000 | *Leymus secalinus* | 83.5 a | *Leymus secalinus* | 66 c |
| | *Artemisia gmelinii* | 70 b | *Artemisia scoparia* | 46.5 d |
| | *Lespedeza davurica* | 46 d | *Lespedeza davurica* | 46 d |
| | *Heteropappus hispidus* | 26 f | *Poa sphondylodes* | 31.5 e |
| | *Astragalus melilotoides* | 25.5 f | *Stipa bungeana* | 17.5 h |
| | *Sconchus oleraceus* | 20 g | *Artemisia lavandulifolia* | 1.5 i |
| | *Artemisia lavandulifolia* | 17.5 h | | |
| 1992 | *Calamagrostis epigeios* | 92.5 a | *Calamagrostis epigeios* | 82.5 b |
| | *Poa annua* | 80.5 c | *Poa annua* | 72.5 d |
| | *Leymus secalinus* | 43 g | *Lespedeza davurica* | 50 e |
| | *Artemisia desertorum* | 33.5 h | *Astragalus melilotoides* | 45 f |
| | *Heteropappus hispidus* | 32.5 h | *Astragalus adsurgens* | 23.5 i |
| | *Polygala tenuifolia* | 10.5 k | *Heteropappus hispidus* | 20 j |
| | | | *Polygala tenuifolia* | 6.5 l |

Means were compared using the Duncan's multiple range test. Values with the same letter were not significantly different at $p < 0.05$.

well in 2007–2008), the dominant species of each plant community were *A. desertorum, Poa annua,* and *C. epigeios*. Compared with the importance values of dominant species in the first stage of succession, the importance values of dominant species in this stage decreased significantly. The highest importance value of dominant species was for *A. desertorum* (60), and the importance value of *C. epigeios* decreased from 58.5 in the early stage to 50.5 and 25. *Artemisia desertorum* was upgraded to the dominant species, but its importance value was also lower than the importance values of companion species in the early stage. This showed that this stage was a stage of intense competition among species. *Calamagrostis epigeios* still maintained a strong competitive ability, while *A. desertorum* changed from an early companion species to a dominant species in this period. *Poa annua* became a new dominant species and the importance value of *L. secalinus* decreased sharply, from a dominant species to an companion species.

After 16–18 years of succession (completion of the well in 2000–2002), the dominant species of the plant community were *L. secalinus* and *A. desertorum*, with the importance values of 95 and 75, respectively. The importance value increased compared with the second stage. *Leymus secalinus* has regained its niche in the competition, and *A. desertorum* had maintained a certain competitiveness. At this time, the interspecific competition was more intense. In the first 10 years, other companion species did not grow in the competition, and other companion species appeared in the plant community, such as *A. scoparia*, *Heteropappus hispidus, Plantago asiatica*, *Lespedeza davurica*, *Artemisia gmelinii, Artemisia lavandulifo*lia, etc., of which *A. scoparia* and *A. gmelinii* had higher importance values, while other importance values were lower and less competitive.

Corresponding to the time of vegetation restoration in the mud pool, after 10–11 years of succession, the plant communities outside the mud pool were basically dominated by *A. scoparia* and *A. lavandulifolia*. The importance value of *A. scoparia* was lower than that in the mud pool, and the importance value of *A. lavandulifolia* was higher than that in the mud pool. After 16–18 years of succession, the dominant species of the plant community were the same as those in the mud pool, mainly *L. secalinus* and *A. scoparia*, but the importance value was lower than that in the mud pool. The importance values outside the mud pool were 62.5 and 52.5, respectively, while those in the mud pool were 95 and 75, respectively. This showed that after 10 years of succession, the vegetation recovery in the mud pool had a gradual trend of stability, and the importance values of species were better than those outside the mud pool.

3) The community is gradually stable. After 18–26 years of succession (well completion in 1992–2000), the dominant species of the plant community were mainly *C. epigeios, P. annua* and *L. secalinus*, with the importance values above 80. These species had advantages in both height and coverage. *Poa annua* and *C. epigeios* were transformed from competitive species in the second stage into dominant species in the plant community, while *L. secalinus* had always been a powerful dominant species. After 28 years of competitive succession, the plant community structure had changed significantly, and the early dominant species still maintained a strong advantage, especially *C. epigeios, P. annua* and *L. secalinus*.

At this time, the dominant species in the plant community outside the mud pool were also dominated by *C. epigeios, P. annua* and *L. secalinus*, with the importance values of 82.5, 72.5 and 66, respectively, which were lower than the importance values of the corresponding species in the mud pool.

From the above succession process, it can be seen that the species composition had significant changes at each stage, and the antagonistic competition among species was relatively complex, which could be analyzed from the change trend of the importance value of the main companion species. *Calamagrostis epigeios, L. secalinus* and *A. scoparia* were suitable for the special natural environment in the northwest and north of China, as well as the ecological environment of abandoned drilling mud. They had strong vitality and had basically been in the niche of dominant species in the competitive succession of the plant community.

It could be seen from the recovery process of the dominant species that the species and importance values of the early dominant species in and outside the mud pit were quite different, and the dominant species in the middle and late stages were gradually similar. The difference was that the importance values of the dominant species were quite different: the substances in the mud pit were higher than those outside the mud pit, indicating that the substances in the mud pit were conducive to the growth of species. In addition, there were differences in the stability and richness of the community.

## 3.2 Dynamic changes of ecological functions of plant communities inside and outside the mud pit at different completion time

The dynamic changes in plant community structure can reflect the characteristics of vegetation restoration process to a certain extent (Figures 2–4).

### 3.2.1 Change of the diversity index inside and outside the mud pit at different completion time

With the extension of the recovery period, the diversity index in the mud pit showed an upward trend, while that outside the mud pit was relatively stable (Figure 2). The vegetation outside the mud pit had already adapted to the environment and the plant community was stable, so the diversity index was stable. The habitat in the mud pit changed greatly and the environment in the mud pit was more conducive to the growth of the dominant species. The competitive ability of the dominant species was strong, and the coverage and height advantages were large, which inhibited the growth of other species, resulting in the instability of the diversity index. The plant community was unstable, and the succession of plant communities at different completion times was quite different. This also showed that the mud environment was more conducive to the growth of individual species, such as *P. annua, L. secalinus, etc.*

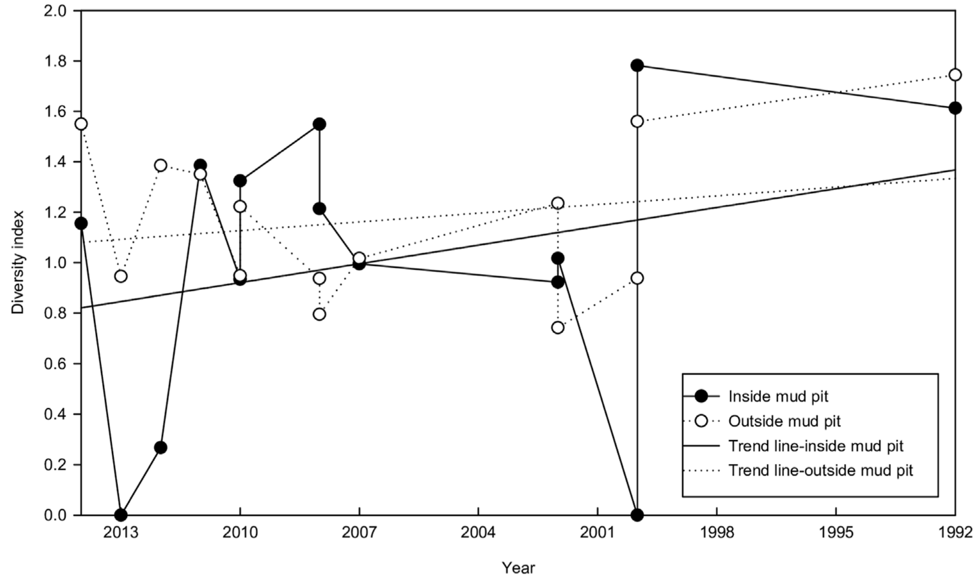


FIGURE 2
Variation of the diversity index inside and outside mud pit at different completion time.

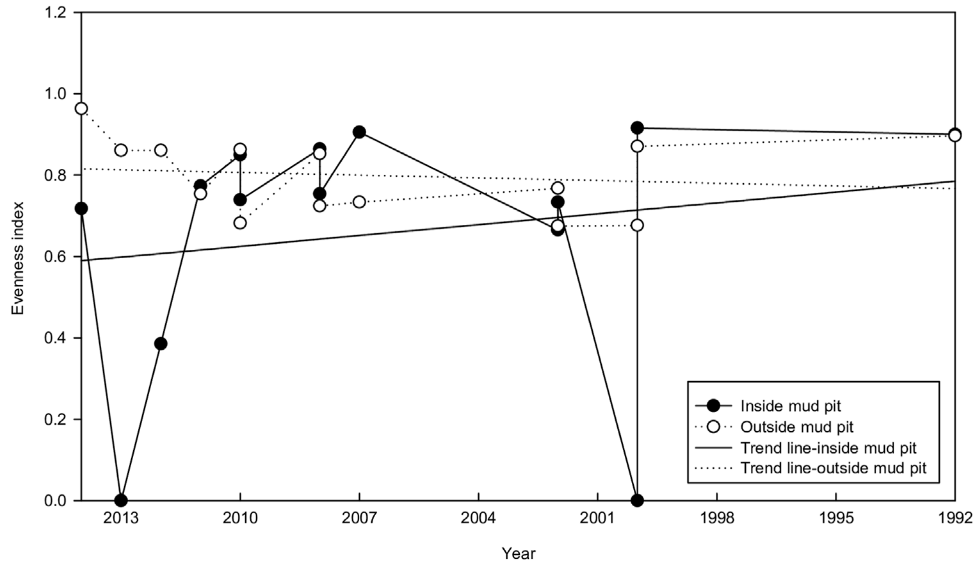


FIGURE 3
Variation of the evenness index inside and outside mud pit at different completion time.

### 3.2.2 Change of the evenness index inside and outside the mud pit at different completion time

With the extension of the succession period, the evenness index in the mud pool showed an upward trend, while the evenness index outside the mud pool showed a gentle downward trend (Figure 3). Figure 2 showed that the diversity index of the mud pit both showed an upward trend, accoding to the method of the evenness index calculation, the number of species in the plant community would affect the result of the evenness index. If the number of species in the plant community was abundant, the reslult of the evenness index would decrease. The plant community outside the mud pit had already adapted to the environment and was stable, so the change of species was stable, the number of species outside the mud pit mostly varied between three and seven, the fluctuation was not significant. Compared with the outside mud pit, the number of species in the mud pit varied between one and seven, the fluctuation was significant. Therefore, the change of species inside and outside the mud pit showed different degrees of stability in some degree. Specifically, the number of species in Shan377# and G41-9# was one, which significantly showed the adaptability of *C. epigeios* and *L. secalinus* to the mud environment in different periods, this also indicated that the mud environment might be suitable for the growth of individual species.

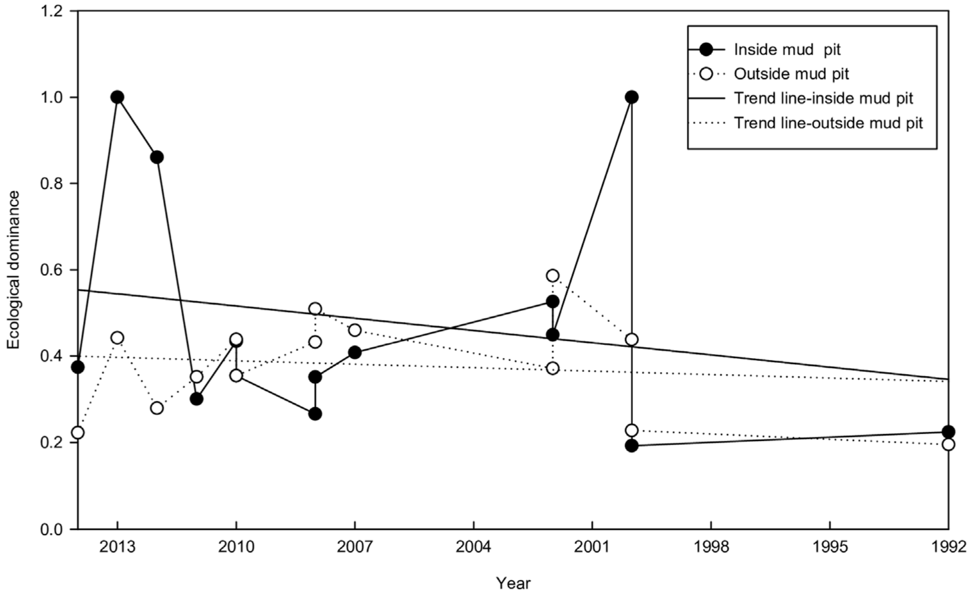


FIGURE 4
Variation of the ecological dominance inside and outside mud pit at different completion time.

### 3.2.3 Change of the ecological dominance inside and outside the mud pit at different completion time

With the extension of the succession years, the ecological dominance inside and outside the mud pool both had a downward trend. In the early stage, the decline degree in the mud pool was greater than that outside the mud pool, and the decline trend in the later stage was basically the same as that outside the mud pool (Figure 4), indicating that the plant community succession in the mud pool in the later stage had also begun to become more stable. For example, the importance value of the dominant species had decreased compared with that in the early stage, and the importance value of the companion species had increased. In the early stage of plant community succession, the species suitable for the mud pool environment grew faster, and the competitiveness was strong. The number of species with high competitiveness reached 10, with high importance values, leading to a high ecological dominance of the plant community. In the middle and late stages of plant community succession, the dominant species succession developed rapidly. After a period of population adaptation, the number of companion species in the plant community was not significantly different from that in the early stage. In the later stage, *C. epigeios* and *L. secalinus* were in a stable position. Every species had its niche, but the importance value was reduced, leading to a gradual decline in the ecological dominance of the plant community.

## 3.3 Dynamic change of production function of plant communities inside and outside the mud pit at different completion time

The dynamic change of vegetation biomass can also reflect the condition of vegetation restoration. The variation trend of plant biomass inside and outside the mud pit was consistent. With the extension of well completion time, the aboveground biomass of plant communities showed an increasing trend (Figure 5). The growth trend of plant biomass in the mud pit was higher than that outside the mud pit, and the biomass in the mud pit at different recovery stages was mostly higher than that outside the mud pit. This also showed that the ecological environment in the mud pit was suitable for the recovery and growth of plants.

## 3.4 Effect of abandoned drilling mud *in situ* treatment on plants

Drilling fluid is an essential and important material in the drilling process. In order to achieve safe and rapid drilling, more and more drilling fluid additives are being used, making the concentration of various components in the abandoned mud higher. Drilling cuttings are equivalent to the accumulation of fresh rock from different regions on the surface. The nutrient elements are more comprehensive and may contain trace elements that are not available in local soil. On the one hand, this may cause environmental pollution, but it may also provide nutrients. Therefore, in order to evaluate the ecological restoration role of dominant species, it is necessary to understand not only their vegetation restoration potentials, but also their possible response to the *in situ* treatment of abandoned drilling mud.

### 3.4.1 Effect of abandoned drilling mud *in situ* treatment on nutrient element in plants

The amount of nutrients in plants reflects the ability of plants to draw nutrients from different soil environments. The nutrient content of plants in different wells is shown in Table 3. The nutrient contents of plants inside and outside the mud pit were different. Compared with the non-mud pit, the total nitrogen

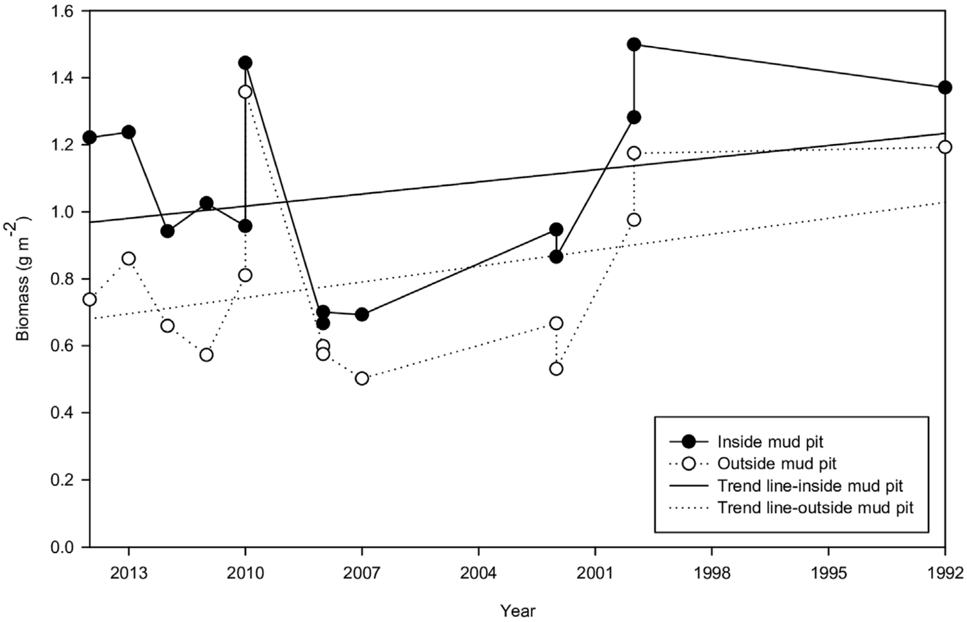


FIGURE 5
Variation of aboveground biomass inside and outside mud pit at different completion time.

TABLE 3 The content of N, P and K inside and outside mud pit.

| | N (mg kg$^{-1}$) | | P (mg kg$^{-1}$) | | K (g kg$^{-1}$) | |
|---|---|---|---|---|---|---|
| | A | B | A | B | A | B |
| Minimum | 3.842 | 5.831 | 0.493 | 0.785 | 11.316 | 5.485 |
| Maximum | 14.869 | 12.960 | 2.300 | 2.397 | 29.838 | 25.390 |
| Mean | 10.118 | 8.578 | 1.251 | 1.422 | 18.828 | 15.087 |
| Standard deviation | 3.073 | 2.377 | 0.503 | 0.486 | 5.625 | 4.967 |
| Coefficient of variation | 30.37 | 27.71 | 40.21 | 34.13 | 29.87 | 32.92 |

A and B represented the sampling location. A represented the location of inside mud pit. B represented the location of outside mud pit. A and B in Tables 4, 5 was the same as Table 3

content of plants in the mud pit increased by 17.95% on average. Among the tested wells, the total nitrogen contents of plants in the mud pit of 9 wells were higher than that of the corresponding non-mud-pit plants. The total phosphorus content of plants in the mud pit decreased by 13.67% on average. The total phosphorus contents of plants in the mud pit of 10 wells were lower than that of the corresponding non-mud-pit plants. Drilling mud had a great impact on potassium content in plants: compared with the non-mud-pit, the plant potassium content in the mud pit increased by 24.80% on average. The potassium contents of plants in the mud pit of 11 wells were higher than that of non-mud-pit plants. Why P behaves differently than N and K? This might be explained from the study of Fu et al. (2022). Fu et al. (2022) gave the basic physical and chemical properties of loessial soil and WBSM samples, which were collected from an active gas welling site in the Changqing Oilfield, also located in the Loess Plateau. The study showed that the contents of N and K in WBSM samples were 1.96 g kg$^{-1}$, 1145.27 mg kg$^{-1}$ respectively, were higeher than the loessial soil, which the contents of N and K were 0.67 g kg$^{-1}$, 93.37 mg kg$^{-1}$ respectively. There was a huge difference in K content. However, the content of P in WBSM sample (1.59 mg kg$^{-1}$) was lower than the loessial soil (5.64 mg kg$^{-1}$).

### 3.4.2 Effect of abandoned drilling mud *in situ* treatment on trace elements in plants

The contents of trace elements zinc (Zn), iron (Fe), copper (Cu) and manganese (Mn) in plants inside and outside the mud pit are shown in Table 4. The normal trace element contents of general plants are Zn 1–160 mg kg$^{-1}$, Mn 14–900 mg kg$^{-1}$, Cu 5–25 mg kg$^{-1}$ and Fe 100–2,486 mg kg$^{-1}$ (Che et al., 2020; Yang et al., 2022). The contents of trace elements in plants inside and outside the mud pit were within the normal range. In the 14 wells tested, the contents of iron and manganese in the mud pit varied greatly. Among them, the contents of Fe in the plants in the mud pit of 9 wells were lower than that of the non-mud pit, with an average decrease of 21.26%. In G41-9# well, the content of Mn in the mud pool was higher than that in the non-mud pool plants, with an average increase of 53.998%. The content of zinc and copper had little change. The contents of Zn in the plants in mud pools of 8 wells were higher than that in non-mud pools, with an average increase of 2.43%. In 10 wells, the contents of Cu in the plants inside the mud pit were higher than that outside the mud pit, with an average increase of 0.4%. The study of Wang et al. (2022) showed that the average total Cu, Zn concentration in soils on the Loess Plateau was 22.5 mg kg$^{-1}$, 69.1 mg kg$^{-1}$, respectively. The study of Fu et al. (2022) showed that the average total Cu, Zn concentration in WBSM samples was 23.5 mg kg$^{-1}$, 506.7 mg kg$^{-1}$, respectively. The content in WBSM sample was higher than that in the soil, this could provide plants with more trace elements, thus could lead to a higher content of Cu and Zn in the plants in mud pools. The average total Mn concentration in soils on the Loess Plateau was 537 mg $kg^{-1}$ (Wang et al., 2022), this value was much higher than the value inside the plant body (Table 4). The average total Fe concentration in WBSM samples was 20.31 mg $kg^{-1}$ (Fu et al., 2022), this value was much lower than the value inside the plant body (Table 4). This showed that Fe and Mn in plant body might be affected by soil nutrients and properties (Kalita et al., 2022), plant biomass, plant absorption capacity and plant carrying capacity, etc.

### 3.4.3 Effect of abandoned drilling mud *in situ* treatment on heavy metals in plants

The content of heavy metals in general plants is: Pb 0.1-41.7 mg $kg^{-1}$, Cd 0.2-3 mg $kg^{-1}$, As 0.07-3.83 mg $kg^{-1}$, Cr 0.3-13 mg $kg^{-1}$ (Liu et al., 2009; Yang et al., 2022). The content of heavy metals in all plant samples tested was mostly within the normal range (Table 5), and the maximum value of Cd inside and outside the mud pit was close to the critical value.

The content of heavy metals in plants inside and outside the mud pit of different wells was different. Among the 14 wells tested, As contents of plants in the mud pit of 10 wells was lower than that outside the mud pit, with an average decrease of 44.18%. Cr and Cd contents in the mud pit of 7 wells were lower than those outside the mud pit, with an average decrease of 46.85% and 5.07%, respectively. Cd contents in the mud pit of Tao2-1-25# and Su14-11-37# well were more than twice as high as those outside the mud pit. Pb contents in the mud pit of 7 wells were higher than that outside the mud pit, with an average increase of 4.67%. The Pb content of plants in the mud pit of Su14-11-38#, Wu19-8# and G41-9# well had more than doubled.

## 4 Discussion

### 4.1 Ecological restoration of dominant species

The above comparative analysis inside and outside the mud pit showed that the special ecological environment in the mud pit was more conducive to vegetation restoration. The total coverage, plant height and biomass of the dominant species in the mud pit were significantly higher than those outside the mud pit. The growth of vegetation in the mud pit was better than that outside the mud pit. There were more types of vegetation in the mud pit than outside the mud pit. The species diversity increased and the stability of the ecosystem was enhanced. The dominant species of plant communities were mainly *L. secalinus, C. epigeios* and *A. scoparia*. The study of the dominant species played a guiding role in water and soil conservation and ecological restoration of the well.

There are many studies on phytoremediation of oil-contaminated soil in existing studies (Halwagy et al., 1982; Blanco-Velázquez et al., 2000; Yateem et al., 2000; Al-Ateeqi, 2010; Zhang et al., 2013; Qi et al., 2014; Li et al., 2015; Al-Shehabi and Murphy, 2017; Al-Thani and Yasseen, 2020; Boruah et al., 2020; Al-Ateeqi et al., 2022; Leonid et al., 2023). For example, Li et al. (2015) selected four herbage plants for a pot experiment by setting oil pollution levels of different concentrations, observed the survival rate, plant height, biomass of herbage plants for 70 days, and measured their oil removal rate. They concluded that *Purus frumentum* and *Sorghum sudanense* were suitable remediation plants for oil-contaminated soil in a North China Oilfield. Through field investigations, Qi et al. (2014) selected seven species of weed plants that could grow well on the soil with serious oil pollution, took the seed

TABLE 4 The content of Fe, Mn, Cu and Zn inside and outside mud pit.

| | Fe (g $kg^{-1}$) | | Mn (mg $kg^{-1}$) | | Cu (mg $kg^{-1}$) | | Zn (mg $kg^{-1}$) | |
|---|---|---|---|---|---|---|---|---|
| | A | B | A | B | A | B | A | B |
| Minimum | 132.669 | 160.268 | 35.870 | 24.736 | 1.880 | 3.290 | 8.966 | 13.680 |
| Maximum | 992.242 | 946.077 | 157.856 | 85.003 | 16.400 | 10.400 | 59.009 | 57.744 |
| Mean | 433.495 | 525.646 | 76.757 | 49.843 | 6.450 | 6.424 | 24.613 | 24.028 |
| Standard deviation | 212.324 | 235.571 | 35.467 | 18.613 | 3.890 | 2.024 | 12.836 | 11.197 |
| Coefficient of variation | 48.980 | 44.820 | 46.210 | 37.340 | 60.230 | 31.513 | 52.150 | 46.600 |

TABLE 5 The content of As, Cr, Cd and Pb inside and outside mud pit.

| | As (mg $kg^{-1}$) | | Cr (mg $kg^{-1}$) | | Cd (mg $kg^{-1}$) | | Pb (mg $kg^{-1}$) | |
|---|---|---|---|---|---|---|---|---|
| | A | B | A | B | A | B | A | B |
| Minimum | 0.073 | 0.136 | 0.300 | 0.306 | 0.0297 | 0.0345 | 0.284 | 0.310 |
| Maximum | 0.789 | 1.29 | 2.540 | 5.490 | 2.920 | 3.130 | 2.500 | 1.700 |
| Mean | 0.292 | 0.421 | 1.065 | 1.564 | 0.571 | 0.600 | 0.896 | 0.856 |
| Standard deviation | 0.205 | 0.357 | 0.690 | 1.413 | 0.834 | 0.879 | 0.629 | 0.439 |
| Coefficient of variation | 70.392 | 84.677 | 64.859 | 90.340 | 145.985 | 146.558 | 70.175 | 51.278 |

germination as the ecological indicator, set up culture experiments with different soil oil quality concentrations, and studied the tolerance of weed seeds to oil pollution by observing the daily germination rate and the final germination time. The results showed that *Setaria viridis*, *Medicago sativa*, *Astragalus adsurgens* and *Melilotus officinalis* had strong tolerance to oil pollution stress in the soil of the northern Shaanxi oil field. Based on field investigations, Zhang et al. (2013) determined the content of total petroleum hydrocarbons by gravimetric method, analyzed the absorption of petroleum pollutants by the main herbaceous and woody plants in different oil exploitation areas, studied the absorption and enrichment of petroleum pollutants by plants, and found that A*gropyron cristatum, Aritemisia gemlinii*, H*ippophae rhamnoides* and *Sophora viciifolia* were the dominant plants for remediation of oil-contaminated soil in the loess plateau of northern Shaanxi. The above experimental setup using pot culture and oil pollution level was very effective. In addition to the artificial planting of *M. sativa*, the selection of other remediation plants relied to a certain degree on human nature. The research results of vegetation restoration in this study could provide a reference for the phytoremediation of oil-contaminated soil or abandoned drilling soil in similar areas. Most of the above natural plants could exist in different stages of vegetation restoration in this study, but they were not the dominant species, such as *S. viridis*, *A. adsurgens* and *Artemisia gemlinii*.

The dominant species in this study were the results of the natural recovery of local species, which also showed that these local species were suitable for growing in the ecological environments surrounding abandoned drilling areas, and thus they can make full use of their role in ecological restoration. *Leymus secalinus* has a wide range of habitats, including sandy land, plain oasis and mountain grassland zones, with strong vitality. In combination with resource utilization, we can consider the use of the rhizome or whole grass of *L. secalinus* as a medicine to develop the Chinese herbal medicine industry. As a kind of forage grass that livestock like to eat, *C. epigeios* has tough roots, strong levels of salt and alkali resistance, and high humidity resistance. It is a good material for sand fixation and bank protection. Therefore, *C. epigeios* can be used as fodder, material for sand prevention and embankment consolidation, and also for desertification control in northwest China. *Artemisia scoparia* has certain medicinal and edible value. If the ecological role and economic value of these plants can be fully exploited, the cost of soil remediation can be reduced and the regional environment can be protected.

Blanco-Velázquez et al. (2000) also proposed that a proper selection of native plant species could play a remarkable role in eliminating petroleum contaminated soil. Al-Thani and Yasseen (2020) studied that a native desert plant *S. ioclados* might be a promising phytoremediator in Qatar for the contaminated desert soil. Al-Ateeqi (2010), Al-Shehabi and Murphy (2017), Halwagy et al. (1982) found that *C. conglomeratus, H. salicornicum* and *R. epapposum* could thrive in oil-polluted soils in Kuwait. Kalita et al. (2022) studied that *L. aspera* had phytoremediation potential in crude oil polluted soil.

## 4.2 Ecological effect of abandoned drilling mud

With the rapid development of the oil and gas industry, the number of wells drilled in the Changqing Oilfield will increase by thousands every year, and each well will produce a large amount of drilling waste (Wei et al., 2021). Extensive research has been carried out globally on the treatment of abandoned mud by land tillage. The results show that a large amount of mud enters the soil, and the interaction between sludge and soil will affect the nutritional environment conditions for crop growth (Guarino et al., 2017; Nivedita et al., 2022).

### 4.2.1 Abandoned drilling mud was beneficial to vegetation restoration

Water is the key factor affecting plant growth and community succession in arid and semi-arid regions, and is the carrier of nutrient circulation and flow (Fu et al., 2022). The layered structure formed by the abandoned drilling mud and the overlying soil leads to the discontinuity of soil pores, hinders the infiltration of water in the upper layer, and fixes its water in the upper layer, which has the effect of water storage and moisture conservation, and can promote the growth of vegetation (Ball et al., 2012). The loosening of soil and surface soil removal during drilling changes the soil structure and may promote the growth of vegetation (Brown et al., 2017). In this study, the biomass, coverage and height of vegetation in the mud pit of the well at different completion times were higher than those outside the mud pit. With the extension of succession years, the diversity index and dominance index of the communities in the mud pool had an upward trend, and the ecological dominance of the communities in the mud pool had a downward trend. On the contrary, the diversity index outside the mud pit changed gently. In addition to the increase of the water content of the overburden layer, the drilling mud also contains various organic substances and mineral ions, which greatly increases the soil fertility, provides nutrients for the growth and development of the upper plants, and promotes the renewal and succession of the plant community. For example, in this study, the content of nitrogen, potassium and trace elements in the mud pool was higher than that outside the mud pool. The mud landing treatment method had little impact on the ecological environment, and could be restored in a short time. In addition, the nutrients in the mud pool could promote the vegetation restoration. The growth of vegetation in the mud pool was significantly better than outside the mud pool. Making full use of the mud, which is rich in nutrients, is more conducive to the restoration and protection of the ecological environment (Guarino et al., 2017).

### 4.2.2 Abandoned drilling mud has an impact on the metal content in plants, but no harm

The results of this study showed that the content of heavy metals in plants in the mud pit was different from that outside the mud pit due to the elements. The content of Pb in the mud pit was higher, the content of As and Cr was lower than that outside the mud pit, and the content of Cd was not different inside and outside the mud pit. Because of the large coefficient of variation, the content of Cd and Pb in individual mud pits was higher than that outside the mud pit. The enrichment of heavy metals by plants is related to the bioavailability of residual heavy metals in the soil (Hiromi et al., 2015; Leonid et al., 2022). Compared with the geological “endogenous” heavy metals, the “exogenous” heavy metals introduced by human activities are less stable in the soil, resulting in a large variation coefficient of heavy metal content in plants. Although the variation was large, the content of heavy metals in all plant samples tested was mostly within the normal range, and the maximum value of Cd inside and outside the mud pit was close to the critical value. The sampling sites are alkaline soil, which plays a certain role in blocking the migration of heavy metals in soil, thus reducing the absorption of heavy metal ions by plants (Kalbitz and Wennrich, 1998; Dermatas and Meng, 2003; Antoniadis et al., 2008). Secondly, organic matter, such as humic acid, contains a large number of organic ligands that can cooperate with heavy metals to reduce their migration in soil. Producing a large amount of substances in the drilling process can fix the heavy metals in the abandoned mud to a certain extent, thus affecting the migration of heavy metals in plants (Dermatas and Meng, 2003). Moreover, the increase of aboveground biomass of plants in the mud pit may also lead to the decrease of the average content of heavy metals in plants. Alternatively, the availability of heavy metals in calcareous soils in the north has been greatly reduced, resulting in the deactivation of heavy metals. The mud landing treatment method uses the curing agent cement, lime, and humic acid to wrap heavy metals, which passivate and complex heavy metals. With the dilution effect of the soil, the activity of heavy metals can be further reduced.

### 4.2.3 Abandoned drilling mud has potential for resource utilization

The resource utilization of mud must meet certain conditions. For example, the soil environmental quality after mud enters the soil must be safe and free from pollution. At present, the additives in the drilling fluid of the Changqing Oilfield are mostly the nutrients necessary for plant growth. The additives in the drilling fluid contain a large amount of humic acid, starch, sawdust and other organic substances, which are excellent materials for fertilizing the soil (Wang and Hao, 2021). The additives in the drilling fluid include a large amount of bentonite, carboxymethyl cellulose and polyacrylamide, which are good soil water-retaining agents and modifiers, especially beneficial to the improvement of sandy land and the restoration and protection of the ecological environment in the Changqing oil and gas region (Fu et al., 2022). The additives in drilling fluid also contain a large number of minerals, which are nutrient elements for plant growth, such as potassium, zinc, boron, manganese, iron, calcium, etc. These elements are very rich, especially the high content of potassium, which is conducive to improving the quality of agricultural products. There are many kinds and rich contents of nutrient elements in mud. The content of organic matter in mud is as high as 2.3%, which is twice that of local loess and 3-5 times that of sand loess. The content of zinc in mud reaches 67.16 $mg\ kg^{-1}$, and the content of copper reaches 41.96 $mg\ kg^{-1}$. Under this condition, the content of mineral nutrients absorbed by plant roots in mud is high and the production capacity is strong. The soil improved by mud has good structure and is suitable for plant growth (Bauder et al., 2005; Brunori et al., 2005). We should make full use of this precious resource and make it play its due role in agricultural and animal husbandry production and ecological environment governance.

## 5 Conclusion

The *in situ* treatment of abandoned drilling mud increased the above-ground biomass and the importance values of species, improved the species diversity in the well, and accelerated the process of vegetation restoration. Abandoned drilling mud increased the content of nitrogen, potassium and trace elements in plants in the mud pit. The content of heavy metals in plants inside and outside the mud pit had little difference. There was a certain amount of heavy metals in plants inside the mud pit, but they were harmless. Abandoned drilling mud has the potential of resource utilization without causing soil pollution.

Based on the investigation and analysis of this study, it is necessary to further study the effects of drilling mud on crops using field-based research in the future, it will be a continuation of this research on a larger scale, further investigations are warranted to ensure overall safety and wellbeing of the ecosystem. It is also necessary to clarify the law of material movement of mud in the mud pool and to pay attention to the study on the adsorption and desorption mechanism of elements under the *in situ* treatment of abandoned drilling mud, and carry out the research on the comprehensive treatment technology of mud, to improve the comprehensive treatment, resource utilization, disposal economics and the environmental safety of abandoned drilling mud.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

SW: Writing–original draft, Writing–review and editing. MH: Investigation, Writing–review and editing.

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## Conflict of interest

The 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.

## Publisher's note

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