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Research Progress on the Properties of Sediment in Coal Mining Subsidence Ponds

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Abstract: In recent years, with the large-scale exploitation and utilization of coal resources in China, ecological and environmental issues in coal mining areas have become increasingly prominent. As typical surface subsidence water-accumulating landforms, coal mining subsidence ponds have sediment with dual functions of a pollutant "sink" and a potential "source", playing a pivotal role in ecological restoration and environmental remediation in mining areas. Currently, the sediment in coal mining subsidence ponds is characterized by complex composition, high pollution load, and highly variable physicochemical properties, posing significant challenges for precise analysis and effective management. Therefore, this study systematically summarizes the relevant research progress from the perspectives of the variation characteristics of physicochemical properties, trace elements, and environmental risks of the sediment in coal mining subsidence ponds, aiming to provide a scientific basis for the precise assessment and restoration of the ecological environment in subsidence areas.

Keywords: Coal mining subsidence ponds; Physicochemical properties; Sediment

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1. Introduction

Coal resources, as an important basic energy source in China, have played an irreplaceable supporting role in national economic development [1]. However, the problem of surface subsidence caused by long-term large-scale coal mining has become increasingly prominent. A coal mining subsidence area refers to a large area of land subsidence caused by underground coal mining that damages the rock stratum structure, leading to the instability of rock masses in the goaf and surrounding areas, and then triggering continuous movement and deformation of rock strata and the surface (such as cracking, caving, etc.), which is usually referred to as a "coal mining subsidence pond" [2].

In major coal-producing areas around the world, such as China's Huainan-Huaibei, Yanzhou, and Northern Shaanxi mining areas, as well as Poland's Upper Silesian mining area, coal mining subsidence ponds are widely distributed [3–4]. These subsidence ponds collect pollutants from various sources, such as surrounding soil erosion, coal gangue stacking, atmospheric deposition, and industrial and agricultural wastewater, and the sediment becomes the final accumulation reservoir for the above pollutants [5]. Therefore, the sediment is not only enriched with a large amount of organic matter, nitrogen, phosphorus, and other nutrients but also may accumulate various pollutants. Studies have shown that the pollution status of sediment is one of the important indicators for evaluating water environment quality [6].

At present, scholars at home and abroad have carried out extensive research on the water environment of subsidence ponds (such as eutrophication and plankton communities). However, there is still a lack of systematic understanding of sediment, a core substrate with dual functions of "source" and "sink." Therefore, this study intends to systematically summarize the research progress on the physicochemical properties of sediment in coal mining subsidence ponds through literature research.

2. Overview of sediment in subsidence ponds

The sediment in coal mining subsidence ponds is a special loose sediment composed of mineral particles, organic matter, microorganisms, and pollutants, which is formed by deposition at the bottom of water bodies after surface subsidence and water accumulation caused by underground coal mining. Its formation process can be divided into three key stages: first, the material input stage. The material sources of sediment are complex, mainly including initial components such as plow layer soil, vegetation residues, and stripped topsoil in the subsidence area [7]; in addition, solid wastes such as coal gangue and fly ash generated by mining activities, as well as wastewater discharged from industrial and agricultural production in and around the mining area, atmospheric dustfall, and agricultural non-point source pollution (such as chemical fertilizers and pesticides) are also important input sources. Second, the transportation and deposition stage. Under the action of rainfall and surface runoff, the above substances are eroded and transported to the water bodies in the lowest-lying subsidence depressions, and then settle and accumulate under the action of gravity to form the initial sediment layer [8]. Finally, the evolution stage. Sediments decompose and transform through microbial biochemical reactions under anaerobic conditions; the forms of pollutants (such as heavy metals) change accordingly, which may be fixed or activated, and the sediment presents an obvious physicochemical layered structure (such as the oxidized layer and anaerobic layer) [9].

Current research on sediment in coal mining subsidence ponds mainly focuses on pollution characteristics, including the spatial distribution of heavy metals represented by cadmium and arsenic, the occurrence state of persistent organic pollutants (such as OCPs), and the carbon and nitrogen nutrient cycle processes at the sediment-water interface. A large amount of evidence shows that sediment is not only a product of the deposition process but also a "sink" and potential "source" of environmental pollutants in the watershed. Its physicochemical properties, pollution characteristics, and environmental risks are significantly different from those of natural lake sediments, which provides a theoretical basis for subsequent risk assessment and ecological restoration [10].

3. Variation characteristics of physicochemical properties of sediment in subsidence ponds

The physical properties of sediment usually include particle composition, bulk density, porosity, and water content, which collectively determine its structural stability, pollutant migration capacity, and ecological functions. These properties are affected by multiple factors such as coal mining, hydrodynamic conditions, seasonal changes, and human activities. For example, coarse-grained substances such as coal dust and rock debris generated during mining can increase the sand content of sediment and change its structural looseness, while surrounding soil erosion input and biological residues can increase the proportion of silt and organic matter. Water flow velocity affects the particle sorting and deposition process. Rapid accumulation is likely to form a weak layer with mixed structure and poor sorting, while surge-disturbed areas promote the increase of sediment compactness [11]. Dong et al. found that resuspension-deposition events can change the particle size distribution of suspended sediments, promote flocculation, and thus enhance the continuous release of hydrophobic organic pollutants [12]. Wu et al. found that the biofilm formed by the long-term attachment of algal mats on the sediment surface can promote the transformation of sediment from aerobic to anoxic and even anaerobic states, and such exogenous membrane structures significantly interfere with the material diffusion process at the sediment-water interface [13]. Yang Yunping et al. pointed out that, affected by the expansion of human activities, the particle size of sediment shows an increasing trend [14]. In addition, dry-wet alternation caused by seasonal water level fluctuations can change the consistency and bulk density of sediment; human activities such as photovoltaic power station pile foundation construction and dredging operations can also directly disturb the sediment, destroy the original structure, and aggravate resuspension [15]. Dang Mengjiao et al. found that the blocking effect of photovoltaic panels leads to an increase in fine-grained sediment (refinement) under the panels, while the proportion of coarse particles increases (coarsening) in the inter-panel areas, thereby reshaping the initial particle composition of the sediment [16].

Chemical properties (such as total nitrogen, total phosphorus, organic carbon, pH, Eh, and heavy metal elements) are the core components of the sediment properties in coal mining subsidence ponds, playing a key role in regulating the migration and transformation of pollutants. Among them, the drastic dissipation of organic matter is one of the most significant chemical characteristics of sediment in subsidence ponds, and nutrients such as nitrogen and phosphorus show an obvious enrichment trend in the sediment. Fan Tingyu et al. found that the organic matter content of sediment in subsidence ponds is 80%–95% lower than that of surrounding soils, while the average contents of total nitrogen (TN) and total phosphorus (TP) are about 20% and 5.35% higher than those of surrounding soils, respectively [17]. This enrichment phenomenon is mainly attributed to the “sink” function of coal mining subsidence ponds as the terminal of regional water systems. More importantly, driven by factors such as wind-wave disturbance, water temperature rise, or benthic organism activities, the sediment is exposed to an oxidizing environment, prompting nutrients to be re-released through the sediment-water interface, thereby causing eutrophication of the water body. Li Jianchao et al. showed that environmental temperature significantly affects the concentration of organic pollutants in sediment interstitial water, with higher temperatures corresponding to higher pollutant concentrations [18].

The pH and Eh in the sediment of coal mining subsidence ponds show significant vulnerability and instability. On the one hand, the pH and Eh of sediment are generally lower than those of surrounding soils; on the other hand, their buffer system capacity is limited, and they are extremely prone to fluctuations due to external disturbances. Seasonal thermal stratification may occur in the water bodies of subsidence ponds, aggravating the anoxic phenomenon in the bottom layer and leading to a further decrease in Eh value. Such drastic fluctuations in pH-Eh conditions directly and sensitively regulate the forms and solubility of heavy metals, the valence states and release fluxes of nutrients, and microbial metabolic pathways, thereby amplifying the uncertainty of environmental risks. Zhang Yongpeng found that different types of photovoltaic utilization models significantly change the pH background of sediment in subsidence ponds: floating photovoltaic ponds have the highest pH (about 8.5) due to the coverage effect, followed by non-photovoltaic ponds, and columnar photovoltaic ponds are between the two; this pH gradient has been confirmed to be a key environmental factor regulating the distribution of heavy metals [19]. Wang Feng et al. pointed out that fluctuations in the salinity of overlying water can also change the pH and Eh of sediment, and significantly affect the microbial community structure and metabolic activity [20].

4. Variation characteristics of trace elements in sediment in subsidence ponds

The content, form, and distribution of trace elements (especially heavy metals) in the sediment of coal mining subsidence ponds are the keys to evaluating their environmental risks, which are jointly driven by the physicochemical properties of the sediment itself (such as pH and organic matter content), external environmental factors (such as seasonal changes, precipitation, and human activities), and biological activities. Common heavy metal elements (Cd, Pb, Zn, Cu, As, Hg, etc.) in the sediment of coal mining subsidence ponds generally show an enriched state. For example, Chen Tong et al. found that the sediment of the sedimentary water body formed by coal mining in the Huainan Panji mining area shows significant accumulation of three trace elements: Cu, Zn, and Cd, with Cd being the most prominent [20]. Ou Jinping et al. (2018) studied the Huainan Guqiao coal mining subsidence area and found that heavy metals in the water body of the subsidence pond are enriched to a certain extent, and their mass concentrations show an increasing trend and consistent changes in the overlying water-interstitial water-sediment [22]. Zhang Yongpeng (2022) found through seasonal monitoring that the average mass concentrations of Cd, Cr, Ni, and Pb in the subsidence water body in winter are higher than those in summer, indicating that heavy metal concentrations are significantly affected by precipitation [19]. Wang Xingming et al. pointed out that the concentrations of Cr, Mn, and Zn in photovoltaic subsidence ponds are significantly different, and are affected by the construction of different types of photovoltaic power stations, usually showing that the concentrations in floating photovoltaic power stations are higher than those in columnar ones [23].

The distribution of heavy metal elements in the sediment of coal mining subsidence ponds shows significant spatial heterogeneity. In terms of horizontal distribution, the concentration of heavy metals in sediment in areas close to mining area sewage outlets, coal gangue yards, and main traffic arteries is significantly higher than that in the central area of the subsidence pond [24–25]. In terms of vertical distribution, the concentration of trace elements in sediment usually decreases with the increase of depth, accompanied by stratification. For example, Luo Jianwei et al. studied the heavy metals in sediment of the Panyi coal mining subsidence area and found that the surface concentration of heavy metals is higher than that in the middle and bottom layers [26]. The concentrations of Cd, Zn, and Hg exceed the background values of water body sediments in Huainan by 6 times, 5 times, and 4 times, respectively.

5. Variation characteristics of environmental risks of sediment in subsidence ponds

The environmental risks of sediment in coal mining subsidence ponds are affected by both natural evolution and human activities: on the one hand, sediment adsorbs and enriches heavy metals and nutrients from mining, agriculture, and atmospheric deposition; on the other hand, when environmental conditions change, these accumulated pollutants may be reactivated and released, posing a persistent ecological threat. Its main environmental risks are manifested as heavy metal pollution risks and organic pollutant pollution risks. Heavy metals have the characteristics of toxicity, irreversibility, and persistence [27–28]. When the environmental conditions of sediment change (such as a decrease in pH value or a change in redox potential), the enriched heavy metals can be released from the sediment to the water body, and then absorbed by aquatic organisms, and migrate to animals and humans through the food chain, seriously threatening human health [19]. For example, Cheng Junwei et al. studied the Maoshi molybdenum mining area in Guizhou and found that the comprehensive pollution index of the entire molybdenum mining area is far beyond the severe pollution standard [29]. The sediments in the study area are seriously polluted by a variety of heavy metals, and the ecological risk is high.

In addition to heavy metals, organic pollutants are also an environmental risk factor that cannot be ignored in the sediment of coal mining subsidence ponds, most of which have potential hazards such as carcinogenicity, teratogenicity, and mutagenicity. When the water body is disturbed, organic pollutants in the sediment may be re-released to the water body, thereby causing secondary pollution. Qiu Haoran found that the total residual amount of 14 PCB congeners in the sediment of the Huainan Panyi coal mining subsidence area ranges from 3278 to 5973 ng/kg (dry weight), with an average of 4339 ng/kg [30]. In addition, the coexistence of organic pollutants and heavy metals may produce complex combined pollution effects such as synergy, addition, or antagonism. Their combined toxicity risks are still a weak link in current research and urgently need to be given great attention.

In summary, the study of sediment physicochemical properties is of great significance for coal mining subsidence water areas in China. The research on the properties of sediment in coal mining subsidence ponds reveals its complex physicochemical characteristics, trace element enrichment, and significant environmental risks. It can be seen that the complexity of sediment properties in subsidence ponds leads to the complexity of the sediment ecological environment, and the mechanisms involved need to be further revealed.

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