Research on Resource Utilization of Sludge Carbonization Products

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Abstract The resource utilization of sludge can effectively achieve the regeneration and utilization of resources, and promote sustainable economic development. Sludge carbonization is a sludge treatment and disposal technology with broad application prospects, and its products have shown significant resource potential in land use, fuel utilization, and other fields. At present, China still faces some challenges in the resource utilization of sludge carbonization, such as issues related to heavy metal stability and outdated standards. In the future, it is necessary to further strengthen research, improve the standard system, and promote the widespread application of sludge carbonization technology, so as to achieve the goals of sludge reduction, harmlessness, and resource utilization and support the development of circular economy.

Key words Sewage sludge; Sludge carbonization; Land use; Resource utilization

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Sludge is an organic solid waste inevitably produced in sewage treatment. If it is not properly treated, it will cause direct or indirect harm to the ecological environment and human health. The treatment and disposal of sludge in sewage treatment plants has become an extremely urgent issue currently faced by China's water industry[1-3]. During the "14th Five-Year Plan" period, China has planned to accelerate the filling of the sludge disposal capacity gap in cities and counties. In the next ten years, it is necessary to fully achieve harmless sludge disposal and significantly improve the level of resource utilization of sludge. In the *Implementation Plan for Harmless Treatment and Resource Utilization of Sludge* jointly issued in September 2022, it was clearly stated that it is needed to actively promote the land use of sludge, promote the recovery and utilization of energy and materials, explore the establishment of an industry acceptance mechanism, and smooth the market outlet for sludge resource products[4]. Extracting valuable components from sludge through scientific means can effectively reduce energy consumption and achieve the goal of resource utilization of organic solid waste. This points out the direction for sludge treatment and disposal. Meanwhile, the resource utilization of sludge can also increase added value, create economic benefits, and promote the development of circular economy.

1 Characteristics of sludge carbonization

Since the 1990s, countries such as Europe, the United States, and Japan have systematically studied sludge carbonization, and gradually formed relatively a mature sludge treatment and disposal process[5-6]. Moreover, this process is highly consistent with China's current "green, circular, low-carbon, and ecological" development requirements[7]. As of July 2025, through a search on CNKI, it is found that there were only 109 359 journal articles on the theme of "sludge" and only 173 journal articles on the theme of "sludge carbonization". The proportion of studies on sludge carbonization in the sludge field was only 0.158%, indicating a relatively low level of attention. However, after more than ten years of technology introduction and independent research and development, more than ten projects of sludge carbonization in Kaili of Guizhou Province, Wuhan of Hubei Province, Zigui of Hubei Province, and Dongguan of Guangdong Province in China have been put into operation currently[8], and have achieved good operational results in soil improvement and landscaping. With the increase in the number of operating projects, the resource utilization of sludge biochar has gradually exposed some problems, and has become a focus of attention in the industry[9-10], which is related to the application and promotion prospects of this technology.

For instance, Chongqing is gradually forming a treatment and disposal technology route featuring the coordinated development of cement kiln co-incineration, sludge composting, thermal drying, cogeneration of heat and power, and incineration for brick-making and ceramsite production. In 2023, the first sludge treatment plant in Chongqing that adopts carbonization technology was completed, with a designed daily treatment capacity of 50 t. The slud-based biochar after drying and carbonization treatment can be used as garden greening soil, ceramsite, *etc.* It can effectively achieve the reduction, harmlessness and resource utilization of sludge, forming a good case. At the same time, it has also exposed certain problems, such as the poor disposal of the later products. The products generated by sludge carbonization treatment is called sludge-based biochar, pyrolysis carbon or carbon residue[11-12].

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They not only retains some characteristics of sludge but also take into account the properties of biochar. Meanwhile, they retain some nutrients such as nitrogen, phosphorus and potassium in sludge, and also have the characteristics of biochar such as large specific surface area, high fixed carbon content and stable properties[13-15].

2 Resource utilization of sludge carbonization products

2.1 Resource utilization in land Sludge carbonization products are rich in nutrients such as nitrogen, phosphorus and trace elements that are essential for plant growth, and has good adsorption properties. Therefore, they can be applied in fields such as soil improvement, landscaping and soil remediation. It is reported that sludge carbonization products can promote soil improvement and nutrient absorption, enhance soil fertility, promote plant growth, and increase crop yield[16-17].

Biochar as soil conditioner is conducive to use and improvement of marginal land, especially suitable for the improvement of acidic soil, which helps achieve sustainable development of gardens, agriculture and the environment. Therefore, the land resource utilization of sludge biochar is one of the important development directions in the field of sludge treatment. However, there is still considerable room for improvement in the resource utilization of sludge biochar in China. The progress of related research and standard development is relatively lagging behind. Currently, Anhui, Shanghai and other places have issued the *Technical Regulations for the Application of Sludge Biochar in Landscaping*, which initially clarify the sludge carbonization process and substrate ratio, further promoting the application of sludge biochar in landscaping[18].

However, sludge contains a certain amount of heavy metals, and they are mostly non-volatile. During the carbonization process, they mainly remain in the carbonization products, and are concentrated and enriched with the increase of pyrolysis temperature. At the same time, heavy metals are effectively passivated and fixed[19-20]. Hence, before the use of carbonization products, the release of heavy metal elements should be clarified. At present, research on the stability of biochar materials mainly focuses on the study of agricultural and forestry waste biochar[21-22]. Although the stability of biochar materials themselves is relatively good, long-term environmental effects may cause certain changes in their physical and chemical properties[23-24]. Moreover, the response effects of different types of soil on the release of heavy metals from sludge biochar are still different, and the release mechanism remains to be further explored and studied. Thus, the stability of sludge biochar and its long-term environmental behavior should be discussed further.

2.2 Resource utilization of fuel from sludge carbonization products Since 2010, the resource utilization of fuel has been one of the main directions for the utilization of sludge carbonization products in Japan. For instance, the *Technical Manual for Sludge Thermal Decomposition Fuel System* released by Japan in 2010, the technical research on sludge carbonization was systematically summarized[25-26]. In 2014, the *Solid Fuel for Sewage Sludge* (JIS standard) was released, and clearly classified sludge biomass fuel into two grades based on total calorific value, including BSF grade (calorific value ≥8 MJ/kg) and BSF15 grade (calorific value≥15 MJ/kg). It clearly stipulates that the moisture content of solid fuel must be less than 20%[27]. In 2015, the *Technical Guidelines for the Energy Utilization of Wastewater Sludge* was revised, and the energy utilization technology of sludge was introduced. As the content of organic matter dry basis sludge in Japan is approximately 80%, which is relatively high overall[28]. Therefore, sludge carbonization treatment technology is one of the key low-carbon technologies recommended by Japan. However, the content of organic matter in sludge in China is relatively low, and there are few cases where sludge carbonization products are used as fuel. Among them, the sludge carbonization project in the north of Economic and Technological Development Zone of Changsha (45 t/d, put into operation in 2018) involves the co-carbonization treatment of sludge and agricultural and forestry organic solid waste. The carbonized product has a relatively high calorific value, and is used as fuel in a power plant for co-power generation. The Institute of Urban Environment, Chinese Academy of Sciences, has co-pyrolyzed sludge with other organic waste, and established a demonstration device for the co-pyrolysis and carbonization of dehydrated sludge and biogas residue, providing a demonstration experience for the promotion and application of the technology for the co-resource utilization of sludge and kitchen anaerobic biogas residue. However, the resource utilization of fuel from sludge carbonization products still needs to be studied further.

2.3 Utilization of sludge carbonization products in wastewater treatment Sludge carbonization products have porous structure, large specific surface area and stable structure, so they play a significant role in the field of wastewater treatment[29]. In the field of sewage treatment, they can effectively adsorb inorganic pollutants (heavy metals) and organic pollutants in sewage, and has a good application prospect[30]. For example, the oxygen-containing functional groups on the surface of biochar made from coconut shells could absorb rhodamine B, with the adsorption capacity of 714 mg/g. The surface functional groups of biochar made from walnut shells are rich in mesoporous pores, and the removal rate of hexavalent chromium could reach over 98%, with a very significant effect. At present, commonly used adsorbents in sewage treatment include activated carbon, alumina, and other active inorganic oxides and resins, *etc.* These materials have been proven to have a good adsorption effect, but their application in production is severely restricted by factors such as high cost, high technical requirements, and strict preparation conditions. Therefore, low-cost carbonization products have a considerable market demand.

2.4 Resource utilization of sludge carbonization products in other aspects In addition to land resource utilization and fuel resource utilization, sludge carbonization products can effectively adsorb substances such as SO_2 and H_2S in the air and improve the quality of the atmospheric environment in the field of waste gas treatment. In the field of soil remediation, they can significantly enhance the fertility and arbon sequestration capacity of soil[31], which is conducive to achieving carbon neutrality. At the same time, some studies have used sludge carbonization products as sludge dewatering aids and aerobic fermentation auxiliary materials[32], all of which have achieved a good effect. Sludge carbonization products can also be used as partial fillers for building materials for resource utilization. The resource utilization of sludge carbonization products is multi-faceted, and their utilization value can be developed by combining with different application fields.

3 Summary and prospects

In recent years, with the continuous increase in the output of urban sludge, its treatment and disposal have risen from "end-of-pipe treatment" to a core issue for the sustainable development of the industry. The importance of sludge treatment and disposal technology has become increasingly prominent. This not only concerns the sustainable development of the industry but is also the key to resolving potential environmental risks. Sludge carbonization technology has rapidly gained popularity due to the concept of "treating waste with waste and turning waste into treasure". Its products have demonstrated unique effects and great potential in multiple aspects such as soil improvement, production of organic fertilizers, remediation of contaminated sites, substitution of building materials and fuels, and serving as high-performance adsorbents.

The land resource utilization of sludge carbonization protects is taken as an example, and the long-term behavior of sludge carbonization products in the soil environment has attracted much attention. With changes in environmental conditions, the carbonized products will gradually age. Hence, it is urgent to carry out multi-dimensional comprehensive research, construct a multi-dimensional research paradigm of "time – space – interface", deeply reveal the stability mechanism and heavy metal release mechanism of sludge biochar, and further clarify its stability, release of heavy metals, and potential impact on soil environment. In the future, it is needed to further enhance scientific research and accelerate the wide application of sludge carbonization technology, so as to achieve the goals of sludge reduction, harmlessness and resource utilization, and inject strong impetus into the development of circular economy.

The resource utilization of sludge carbonization products as fuel can be carried out from multiple dimensions of "high value, large scale, and low carbonization". Sludge charcoal can be used to replace part of coal, and sludge can be carbonized in a coordinated manner with organic solid waste from agriculture and forestry. The addition ratio can be optimized to maximize its combustion efficiency and particle calorific value, and the overall operation should be considered for low carbonization.

In the treatment of wastewater, sludge carbonization products can adsorb one or several specific heavy metals. In reality, heavy metals and organic pollutants mostly coexist, and are affected by multiple factors such as acidity and alkalinity, temperature, and pollutant concentration. Therefore, it is necessary to study the treatment effect of wastewater under "multi-dimensional and multi-environment" conditions and carry out experiments – small-scale tests – pilot-scale tests in combination.

The resource utilization of sludge can enhance its added value and market competitiveness, and help form an industrial chain. Research on sludge carbonization products should be combined with the demands of multiple fields and carried out from multiple aspects and perspectives to promote the resource utilization of organic solid waste and at the same time drive the development of a circular economy.

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