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Research on Green and Environmentally Friendly Technologies for the Disposal of Earthenware Waste

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Abstract: In China, the craftsmanship of earthenware boasts a time-honored history and profound cultural heritage, while globally, scholarly inquiries into earthenware technology remain vibrant. Nevertheless, with the expanding production and utilization of earthenware, the volume of waste generated throughout its entire life cycle—spanning raw material extraction, shaping, firing, and the breakage and discarding of finished products—has been on a steady annual rise. Conventional disposal methods, such as land filling and incineration not only squander valuable resources but also inflict environmental pollution, which runs counter to the contemporary ethos of green development. This study undertakes an analysis of the sources, characteristics, and environmental impacts of earthenware waste, while simultaneously exploring the advancements in green and eco-friendly disposal technologies both domestically and internationally. These technological avenues encompass resource recycling, energy recovery, and the fabrication of advanced materials, among others. Through a comparative examination of case studies across different countries and an assessment of the practical operability of relevant technologies, this study proposes a tailored green disposal pathway aligned with China's national context. The objective is to facilitate the green transformation of the earthenware industry and underpin the achievement of sustainable economic development.

Key words: Earthenware waste; Green and eco-friendly disposal technology; Green transformation; Circular economy; Resource utilization

1 Introduction

China stands as the world's premier hub for earthenware manufacturing and production, leading globally in both annual output and export volume. The craftsmanship of earthenware carries a profound historical legacy, with traditional techniques dominating the production process in most regions. However, the earthenware production cycle is plagued by a suite of environmental challenges: suboptimal control over product plasticity, improper regulation of temperature

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and humidity, and flawed heating rates, for instance, all conspire to reduce product yield and elevate the proportion of earthenware waste. Compounding these issues, conventional disposal methods exacerbate resource wastage and environmental contamination. Against this backdrop, this study highlights the critical importance of researching green and environmentally friendly technologies for earthenware waste disposal, puts forth targeted countermeasures and recommendations to address existing bottlenecks, and seeks to propel the further development of the earthenware industry.

Currently, academic research on environmental technologies for solid waste in the ceramic industry—both domestically and internationally—is relatively robust, yet studies specifically focusing on earthenware waste disposal remain scarce, leaving conspicuous research gaps. Firstly, foundational theoretical research on earthenware waste disposal is inadequate. While China has conducted theoretical investigations into the high-efficiency utilization of ceramic slag, key aspects such as the characteristics of earthenware slag, its compositional analysis, and the transformation mechanisms of various minerals during resource recycling remain insufficiently delineated. Secondly, although resource recycling technologies such as high-temperature sintering and low-temperature melting can be applied to earthenware waste disposal, they are beset by prominent challenges, including exorbitant costs and excessive energy consumption. Furthermore, the earthenware industry lacks unified technical standards and specifications for waste disposal, resulting in significant disparities in treatment processes and product quality across enterprises.

To address these research gaps, the earthenware industry should collect samples of diverse earthenware slags, conduct comprehensive mineral composition testing via X-ray diffraction (XRD) to establish a corresponding database, and design variable experiments to simulate multiple treatment conditions, thereby determining the structural changes of earthenware waste during disposal. For earthenware slag resource recycling technologies, collaboration with research institutions should be pursued to secure funding and develop more economically efficient technologies. Concurrently, the state should promulgate relevant laws and policies, improve the institutional framework, refine standards for earthenware waste treatment, and ensure the effective implementation of these standards.

As an intangible cultural heritage, earthenware serves as a cultural calling card for China on the global stage and occupies an indispensable role in fostering national cultural confidence. However, the traditional craftsmanship of earthenware products remains largely outdated, plagued by an incomplete industrial system and backward high-tech capabilities, which collectively contribute to low product yields. The current industry lacks support for green and environmentally friendly technologies, and the improper disposal of earthenware waste poses tangible environmental risks. By examining the challenges of waste disposal, this study seeks to enhance the competitiveness of the earthenware industry, foster innovation, and ensure compliance with increasingly stringent environmental regulations. It further aims to transform waste into valuable resources, improve resource utilization efficiency, and integrate traditional craftsmanship with modern environmental protection technologies.

The organizational structure of this study is divided into 7 parts. Chapters 1 and 2 focus on the background of earthenware waste, research gaps, and relevant green environmental protection theories. Chapters 3 and 4 analyze the characteristics of earthenware waste and the current application of green environmental protection technologies in the ceramic industry. Chapters 5 and 6 identify the core issues of earthenware waste disposal and propose actionable measures. Chapter 7 serves as the conclusion, summarizing the key findings of the study.

2 Literature Review and Theoretical Foundations

2.1 Research Status in Related Fields

In studies on the economic value of the earthenware industry and regional development, Wu Longyin (2024)[1] took Rong County, Sichuan Province, as a case study to analyze the contribution of the earthenware industry to regional economies, highlighting its pivotal role in boosting employment and driving economic growth. Liao Zhenjie and Chen Jiaming (2022)[2] documented the practical experience of how the characteristic earthenware industry in Rong County, Sichuan, has sustained the stable development of the local industrial economy. People's Daily (2025)[3] published an article titled"'Small Earthenware' Drives a 'Large Industry' in Rong County, Sichuan," which illustrates, from a media perspective, how the large-scale development of the earthenware industry has driven regional economic growth. However, these studies exclusively focus on the economic value and regional driving role of the earthenware industry, failing to address environmental issues related to waste disposal in industrial development. They also lack research on the "synergy between economic growth and green development," thus providing no in-depth industrial-level analysis to underscore the necessity of green disposal technologies for earthenware waste.

In research on earthenware craftsmanship and cultural characteristics, Zhao Honghui (2025)[4] adopted a comparative perspective to explore the technical features of Jianshui purple pottery in Yunnan Province, analyzing the uniqueness of its raw material processing, shaping, and decoration processes. Xiang Bingcheng and Dai Jiang (2011)[5] interpreted the artistic value and technical essentials of the kiln transformation technique for Jianshui purple pottery. Li Maoliang, Chen Shikun, and Li Qing (2023)[6] systematically outlined the traditional production processes and technical characteristics of Longchang earthenware. Zhang Ganghua and Tian Jun (2019)[7] investigated the structure and operational properties of traditional earthenware kilns in Yingjisha County, Kashgar Prefecture. These literatures emphasize the cultural inheritance and technical characteristics of traditional craftsmanship but overlooks the mechanisms of waste generation, the compositional properties of waste in the crafting process, and the role of process optimization in waste reduction. Consequently, green disposal technologies for earthenware waste lack foundational research on their compatibility with traditional craftsmanship.

In the literature on ceramic waste utilization technologies, Lü Zhi et al. (2023)[8] studied the reuse of waste daily-use ceramics in the green bodies of daily-use ceramics, verifying its technical feasibility. Wang Tongyan (2014)[9] analyzed the sources and existing utilization methods of ceramic production waste, summarizing the current technical status and application scenarios. Wang Tongyan (2015)[10] supplemented technical details on the treatment of different types of ceramic waste, deepening the understanding of relevant technologies. Pan Wenhao and Yu Baoyang (2010)[11] explored the application prospects of waste ceramics in concrete-based materials, expanding cross-industry utilization ideas. Lu Shengwu and Zeng Zhixing (2008)[12] verified the feasibility of producing recycled concrete using waste ceramics as aggregates. Wang Ya (2025)[13] studied the application of solid waste resource recycling technologies in environmental protection projects, covering ceramic waste treatment. Zhang Linzhuo et al. (2025)[14] discussed the application of solid waste crushing technology in roadbed filling, providing references for the use of ceramic waste in infrastructure construction. Zhang Weiju et al. (2016)[15] developed a cyclic utilization process for solid waste from ceramic production, achieving 100% recovery of polished sediment sludge, which was granted national patents and certified by the Ministry of Industry and Information Technology. Dong Ting (2013)[16] studied the innovative reuse of ceramic waste from the perspective of the circular economy, integrating technical and economic models. Yang Yun (2014)[17] explored the reuse of ceramic waste in environmental design, expanding its cultural and artistic value. While these studies primarily target waste from modern ceramics, such as daily-use ceramics and architectural ceramics, they offer valuable insights for conducting specialized technical research on the unique composition and morphology of earthenware waste. Nevertheless, these technical studies are limited to single-link exploration and lack the construction of a full-process technical system encompassing “collection-treatment-recycling-utilization” tailored to the earthenware industry.

In research on green supply chains and green low-carbon technologies in the ceramic industry, Guan Xihua (2024)[18] took JY Ceramic Company as a case study to propose optimization strategies and transformation methods for green supply chain management in ceramic enterprises. Liao Ruijin et al. (2025)[19] studied the progress of low-carbon cold sintering technology for zinc oxide-based electrical ceramic composites, focusing on the low-carbonization of modern ceramic production. Yu Juan (2015) researched the application of green design in ceramic design, emphasizing the integration of green concepts in the ceramic product design phase and providing ideas for achieving environmental optimization in the ceramic industry from the design source. Yu Juan (2015)[20] researched the application of green design in ceramic design, emphasizing the integration of green concepts in the ceramic product design phase and providing ideas for achieving environmental optimization in the ceramic industry from the design source.

In summary, the aforementioned literature focuses on the earthenware industry and the green development of the ceramic sector. From an industrial value perspective, they confirm the role of the earthenware industry in driving regional economies and employment, while also outlining the craftsmanship and cultural characteristics of earthenware in different producing areas. From a technical perspective, they have developed diverse utilization pathways for modern ceramic waste (with some achieving a resource recycling closed loop) and explored green supply chain management and low-carbon technologies for modern ceramic enterprises. However, research on green environmental protection technologies specifically for earthenware waste disposal remains scarce, with obvious gaps. On one hand, there is a lack of research on the unique properties of earthenware waste and its craftsmanship, as well as specialized exploration of technologies compatible with the green disposal of earthenware waste. On the other hand, the earthenware industry has yet to incorporate waste disposal into its entire supply chain. A comprehensive green technology framework—encompassing collection, treatment, and utilization under the principles of the circular economy—is still lacking, making it difficult to achieve green and sustainable development in earthenware waste management.

2.2 Related Theories

2.2.1 Circular Economy Theory

The circular economy theory is an economic model characterized by a closed-loop flow of “resources-products-waste-recycled resources”. Its core lies in abandoning the traditional linear economy of “mass production, mass consumption, and mass waste” and instead implementing the 3R principles—Reduce, Reuse, and Recycle—to achieve the integration of efficient resource utilization, pollutant emission reduction, and sustainable economic and social development.

This study can leverage the “3R principles” to construct a technical pathway for earthenware waste disposal. “Reduction” corresponds to optimizing earthenware production processes to minimize waste generation at the source; “Reuse” involves directly transforming intact waste earthenware products into cultural and creative products or horticultural components; “Recycling,” as the core of this study, focuses on high-value conversion technologies for crushed waste, such as the preparation of recycled clay, new building material aggregates, and adsorption materials, thereby forming a closed loop of "earthenware production-waste-recycled resources."

The circular economy theory emphasizes the "synergy between environmental and economic benefits," which can guide the feasibility analysis of this study: it not only elaborates on how disposal technologies reduce environmental pollution but also combines case studies (e.g., Rong County, Sichuan) to analyze the market value of waste resource-recycled products, demonstrating the role of these technologies in supporting the green transformation of the earthenware industry and the sustainable development of regional economies.

2.2.2 Resource Recycling Theory

Green design, also known as ecological or environment-oriented design, is a systematic design methodology that integrates technical, environmental, and economic information throughout a product's life cycle. It applies advanced theoretical approaches to develop products that exhibit superior technical performance, strong environmental compatibility, and sound economic efficiency. This study can adopt the circular design approach of green design theory, which fully considers the feasibility of earthenware waste recycling and further reuse. This ensures the maximization of earthenware waste utilization while minimizing energy consumption and environmental pollution.

3 Characteristics and Classification of Earthenware Waste

3.1 Definition of Waste

In a narrow sense, earthenware waste refers to earthenware products with cracks, breakages, or defects. In a broader sense, it encompasses all earthenware-related materials that lose their original value during the entire life cycle of earthenware products, including production, processing, transportation, use, and discard. Specifically, it includes defective green bodies, broken semi-finished products, cutting waste generated during processing, fired waste products from kilns, and discarded used earthenware products such as pottery jars and basins.

3.1.1 Sources and Classification of Waste

The waste of earthenware is roughly classified into green body waste, which refers to the waste generated before the earthenware is fired and formed. Waste glaze refers to the sewage formed during the production process of earthenware. Fired waste refers to the damage caused during storage, transportation and handling after the earthenware products are fired in the kiln. Sagger waste refers to the tools used for flame isolation during the firing of earthenware, which are discarded due to cracking after multiple firings.

As shown in Figure 1, the export value of China's ceramic industry remained at a high level from 2019 to 2023. The annual export value of China's ceramic industry exhibited significant volatility from 2019 to 2023, with specific figures of USD 25.1195 billion, USD 25.1133 billion, USD 30.6950 billion, USD 31.3220 billion and USD 26.0580 billion, respectively. Among them, during 2021-2022, affected by global supply chain adjustments and phased release of overseas market demand, the export value exceeded the USD 30 billion mark for consecutive years. It reached a historic peak of USD 31.322 billion in 2022, despite the fact that in 2023, due to changes in the international economic and trade environment, high overseas inventory and other factors, the export value adjusted back to USD 26.058 billion, a year-on-year decrease of approximately 16.8%, the average annual export scale of the industry remained above USD

28 billion in the five years, which fully reflects the important position and sustained competitiveness of China's ceramic industry in the global supply chain.

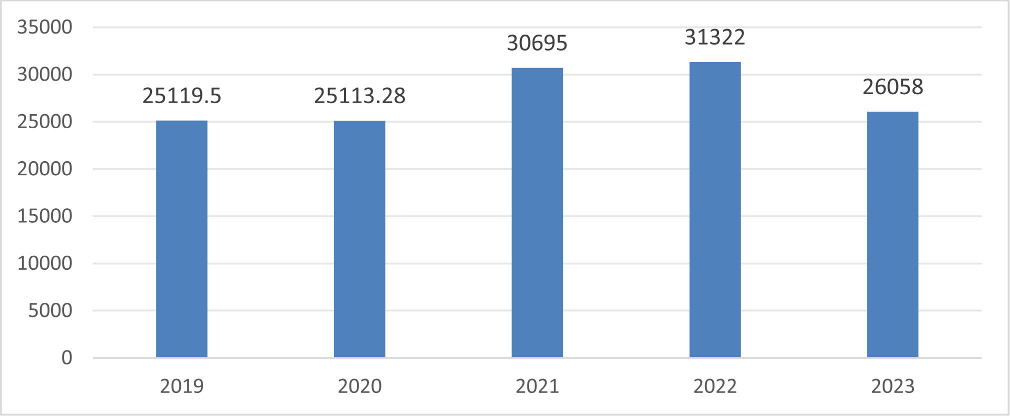

Figure 1 Export value of China's ceramic industry from 2019 to 2023 (in millions of US dollars)

(Data source: National bureau of statistics)

Figure 2 illustrates a gradual decline in national output over the same period. From 2019 to 2023, the national output of ceramic tiles was 8.225 billion square meters, 8.570 billion square meters, 8.174 billion square meters, 7.310 billion square meters and 6.730 billion square meters in sequence. It is worth noting that after reaching a peak high in 2020, the output declined consecutively for three years from 2021 to 2023, and the output in 2023 decreased by approximately 21.5% compared with the peak in 2020. This change is closely related to factors such as domestic real estate market regulation, stricter environmental protection policies, energy structure adjustment and industrial transformation and upgrading. Despite the shrinking trend of output, in terms of absolute scale, the national output of ceramic tiles still remained above 6.7 billion square meters in 2023. Converted by the common specification (800mm×800mm), it is equivalent to an annual output of more than 10 billion ceramic tiles, indicating that China's ceramic tile manufacturing industry still has a huge production capacity foundation and supply capacity.

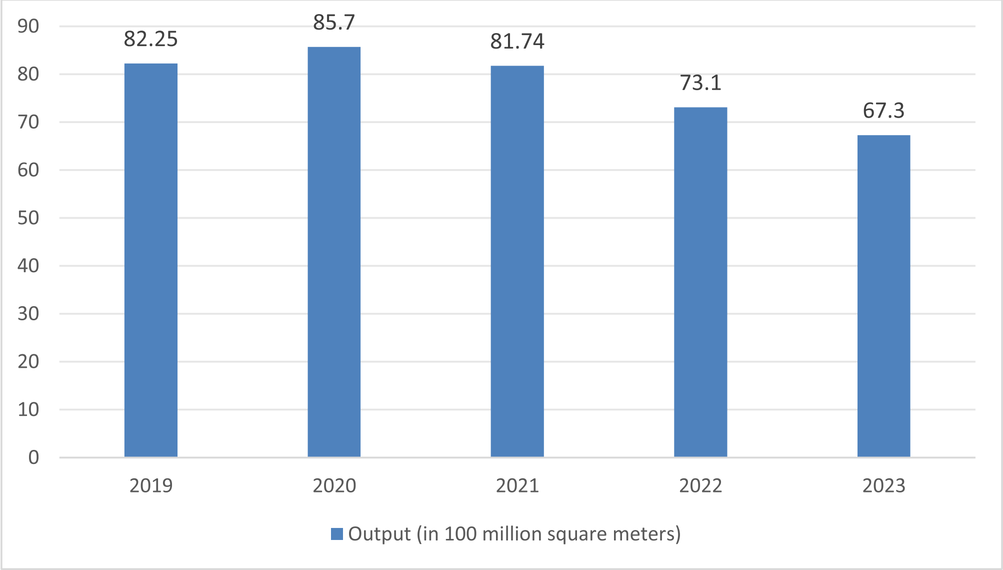

Figure 2 Output of China's ceramic tiles from 2019 to 2023

(Data Source: China Building Materials Industry Planning and Research Institute)

Overall, China's ceramic industry is undergoing a critical transformation stage from "scale expansion" to "quality improvement". The high-level fluctuation of export value reflects the complexity of the international market and the adaptability of the industry, while the rational decline in output embodies the gradual deepening of supply-side structural reform. Driven by the concept of green development, the industry will continue to evolve towards high-end, intelligent and green directions in the future, promoting the further optimization of the global ceramic industry pattern.

It is precisely because of the development of the ceramic industry that the output value of the earthenware industry, which is part of the ceramic industry, has also increased year by year. In its production process, a large amount of waste is generated, including solid waste such as waste mud and waste embryos, liquid waste such as waste water and waste mud slurry, and gaseous waste such as waste flue gas and waste hot gas.

Especially for earthenware mainly made by traditional crafts, the yield is low, and there is more waste. Due to the difference in product qualification rates of various enterprises, the amount of waste porcelain generated varies. At present, the amount of waste porcelain consumed by enterprises themselves is limited, and the additional amount in the formula is only about 3%. Therefore, the waste porcelain of enterprises is piled up like a mountain. Most of the waste porcelain is disposed of as garbage, which not only consumes a lot of manpower, material and financial resources, but also pollutes the environment. China's ceramic industry consumed up to 300 million tons of mineral raw materials annually in 2025 and generated approximately 18 million tons of ceramic waste. Most of these wastes are waste embryos, leftover materials, unqualified products, etc. Moreover, during the use of earthenware, waste will also be generated in cases such as pottery damage and wrong coating.

3.1.2 Current Situation of Earthenware Waste

At present, earthenware production is mainly workshop-based, generally adopting traditional handicraft techniques, with less capital investment and emphasis on the quality rate of finished products. However, its output is far lower than that of large-scale and specialized earthenware enterprises. Therefore, the amount of earthenware waste generated is relatively small, and the pollution space is limited. But due to the traditional craftsmanship, kiln firing produces a lot of harmful gases, the technology for environmentally friendly disposal of waste is inadequate, and the environmental awareness of potters is relatively weak. All these will have a certain impact on the environment. The issue of recycling and reusing earthenware waste cannot be ignored.

The annual output of earthenware workshops generally ranges from 8,000 to 15,000 pieces, with an annual raw material consumption of about 25 to 40 tons and resulting solid waste of approximately 2 to 5 tons. Although this magnitude is only one-thousandth of that of large-scale ceramic enterprises, due to inherent limitations of traditional craftsmanship, the environmental load per unit product cannot be ignored.

In terms of energy use, about 78% of earthenware workshops still rely on traditional firewood kilns or improved coal-fired kilns for firing. Monitoring data shows that particulate matter emissions per ton of pottery fired can reach 3.2 to 4.8 kilograms, sulfur dioxide emissions stand at 5 to 7 kilograms, and the concentration of polycyclic aromatic hydrocarbons in flue gas often exceeds industrial kiln standards by 2 to 3 times. Meanwhile, waste disposal methods in workshop production are relatively extensive. Surveys indicate that over 90% of workshops adopt simple landfilling for waste blanks, and direct discharge of waste slurry still accounts for 34%, leading to suspended solids concentration in surrounding water bodies exceeding standards by 8 to 15 times.

It is particularly noteworthy that there is a dual weakness in environmental protection awareness and technology.

Sampling surveys in multiple traditional production areas reveal that only 22% of practitioners understand relevant regulations on solid waste pollution prevention and control, and the proportion of technical personnel with environmental protection training experience is less than 15%. In terms of waste resource utilization, the average waste reuse rate of workshops is only 12.7%, far lower than the over 35% level of large-scale enterprises, and environmental governance investment per 10,000 yuan of output value is about 80 yuan, less than one-eighth of that of above-scale enterprises.

Although the total pollution from a single workshop is limited, its cumulative effect is significant in spatially concentrated areas. Taking a traditional production area as an example, the annual operation of 50 workshops has led to about 8 hectares of land occupied by waste dumps, emitting 2.3 tons of chemical oxygen demand and approximately 4.2 kilograms of heavy metal lead into the environment each year. Under specific meteorological conditions, its contribution to local PM2.5 concentration can reach 15 to 22 micrograms per cubic meter. These data indicate that the environmental impact of traditional earthenware production has evolved from a "trace and scattered" form to a "locally aggregated" one. It is urgent to adopt systematic solutions, such as establishing regional collaborative treatment mechanisms and promoting cleaner production technologies to achieve green transformation while protecting traditional craftsmanship.

Large-scale and specialized earthenware enterprises have more advanced and complete equipment and technologies to improve efficiency and increase economic benefits. Compared with the output of traditional earthenware production, their output has greatly increased. The quality and yield rate are affected by equipment, which is comparable to or even higher than that of traditional earthenware production. However, the output of earthenware waste is usually positively correlated with the quantity of earthenware production. Therefore, the increase in output also means that the quantity of earthenware waste increases accordingly. For the disposal of these wastes, most small and medium-sized enterprises will carry out recycling according to their own situations, but most of them are discarded as waste. Random dumping, collective stacking or direct land filling of wastes, etc., these non-standard measures have laid hidden safety risks for the natural environment and human development.

3.2 Content of Harmful Substances

In the production process of earthenware, raw materials such as clay used are mostly composed of silicon dioxide, aluminum oxide and other components. However, clay in some areas also contains heavy metal components such as lead and cadmium, and natural minerals also contain a small amount of radioactive substances. For instance, the lead content in some red soil clays in southern China can reach 50-200 mg/kg, significantly higher than the soil background value. In addition, naturally associated radionuclides such as potassium-40, uranium-238, and thorium-232 in clays, though present at low levels (usually with specific activities of uranium and thorium ranging from 40-120 Bq/kg), will remain in the products after high-temperature sintering. This leads to earthenware waste also containing certain radioactive substances. Moreover, during the firing process of earthenware, many manufacturers add lead-containing compounds to lower the firing temperature and thereby improve the yield of qualified products. In addition, arsenic-containing compounds are often used as fluxes to promote better fusion and bonding of raw materials, resulting in a denser structure and greater hardness of the finished earthenware. However, in the earthenware waste produced by the above process, the leachable lead content can reach 5-15 mg/L (more than 5 times higher than the limit specified in the Identification Standards for Hazardous Waste), and the leachable arsenic concentration is about 0.5-2 mg/L. When the waste is stored in open air, approximately 0.8-1.5 kg of lead and 0.1-0.3 kg of arsenic per hectare of the storage yard can migrate through runoff annually under long-term weathering and leaching. More notably, radionuclides will spread with dust during crushing and pulverization; monitoring data shows that the ambient γ-radiation dose rate within 200 meters around the storage yard can reach 0.18-0.25 μGy/h, which is 15-30% higher than the local background value.

These data indicate that improper disposal of earthenware waste not only occupies land resources but also may form composite pollution through multiple pathways, such as atmospheric deposition, water infiltration, and biological enrichment. Currently, it is urgent to establish a precise control system based on material flow analysis and promote the coordinated development of mineralization and stabilization technologies for heavy metal-containing earthenware waste and radioactive classification control standards.

When earthenware waste is randomly discarded into the soil, the heavy metals and radioactive substances it contains are gradually released over time. This process pollutes the soil, disrupts microbial and plant ecosystems, and leads to the accumulation of heavy metals and other harmful substances in plants. Through the spread of the food chain, it will affect the growth and healthy development of other organisms. Moreover, if earthenware waste is close to the water environment, the harmful substances in the waste will enter the water flow. For more than a decade, it has been discharged as waste. 60% of the discharged mud is wastewater dissolved with a large amount of heavy metals and amide organic matter. Each ceramic company discharges about 60,000 tons or more of such mud every year. Entering groundwater with rainwater will cause serious pollution to the surrounding water bodies, seriously affecting the surrounding water environment, leading to the deterioration of water quality, affecting the survival of organisms in the water body, and destroying the balance of the water ecosystem.

4 Green and Environmentally Friendly Disposal Technologies

4.1 Resource Utilization Technology

The traditional landfill and incineration treatment technologies for earthenware product waste will have certain impacts on the environmental ecosystem and resources. In terms of resource utilization technology, we can learn from the treatment of ceramic waste in different countries. In the UK, waste porcelain pieces are crushed, classified by color, and then added to products of the same or similar color to solve the problem of waste porcelain reducing the whiteness of the green body. In China, waste ceramics are classified by material, crushed into particles of different particle sizes by crushers, further finely ground in ball mills, and then processed into standardized recycled ceramic powder. These ceramic powders are compounded with kaolin and feldspar in a certain proportion, and then formed by pulling to make products such as artistic vases and tea sets. By learning from new solid waste treatment technologies, earthenware waste is used to replace disposable fuels, and renewable materials existing in solid waste are used for resource conversion.

The principle of solid waste crushing technology involves decomposing large-volume solid waste into smaller, more uniformly shaped pieces, particles, or powders through mechanical or physical forces. The application of solid waste crushing technology in the green environmental protection research of earthenware waste disposal is based on the modification of the physical properties and performance enhancement of earthenware solid waste materials. The core of this technology lies in reconstructing the particle composition and structural characteristics of earthenware solid waste through mechanical crushing. By crushing the waste into particles of different sizes, it can be recycled and integrated into different materials to form new materials, thereby achieving the goal of "circulation." Earthenware solid waste can draw on this technical theory to provide feasibility support for its disposal.

For glaze waste, the glaze regenerated powder can be ground separately and compounded with new glaze in proportion, so as to reduce the loss of mineral substances, reduce the melting temperature during glaze firing, and further reduce energy loss. The homogenized earthenware waste is artificially crushed by a crusher and screened. There are two processing methods for earthenware solid waste. The first is to crush the waste separately, and the second is to mix the waste with other substances evenly and then crush them together, and then screen them separately. The waste residue is classified and treated according to particle size. Coarse particles and substances such as crushed stone and lime are directly used as roadbed fillers. Medium particles can replace aggregates and be mixed with cement, porcelain stone and other materials, and made into various building materials with high water permeability and high stability by dry pressing. These non-fired bricks are used in building construction. For example, when ceramic is used to replace natural coarse aggregate, its cohesion and flexural strength are not significantly different from those of ordinary concrete. The waste earthenware is crushed into fine particles and filled into the soil, which increases the pore structure inside the soil and enhances the water permeability and drainage of the soil.

4.2 Energy Utilization Technology

The disposal of earthenware waste can be realized by screening waste residue without heavy metal substances, crushing it into particles, and sending it into a circulating fluidized bed incinerator together with other wastes for incineration power generation, so as to achieve volume reduction treatment. Earthenware waste has high thermal stability, which can effectively reduce the risk of slagging in the furnace. It reduces slagging risk by about 40%. Its inorganic components can form the skeletal structure of incineration bottom ash, controlling the loss on ignition of bottom ash below 5%, which meets the requirements of Pollution Control Standard for Domestic Waste Incineration (GB 18485-2014) and provides a physicochemical basis for subsequent preparation of subgrade materials or ceramsite. At the same time, its own inorganic components can be used as the skeleton material of incineration waste residue, which is convenient for the subsequent resource utilization of waste residue. The hot gas generated during incineration, after purification, can be sent into the furnace as fuel for combustion. The steam produced can be used for heating or power generation, realizing cascaded energy utilization. The high-temperature flue gas generated during incineration recovers heat through a waste heat boiler, which can heat cold water for the enterprise's production water, reducing fossil energy consumption.

In terms of energy, earthenware products can also utilize microwave pyrolysis technology for waste with high carbon content. After pyrolyzing it for about 2 hours, crude carbon substances are obtained. Then, water or carbon dioxide is used as an activator, which can be applied in fields such as wastewater decolorization and air purification. By adjusting the pyrolysis temperature, substances in these earthenware products can also be converted into black substances such as carbon black, and valuable parts in the waste can be recovered for use as rubber reinforcing agents and ink pigments.

4.3 Biochemical Conversion Technology

With the development of the earthenware industry, more and more earthenware ~~craftsmen~~, artisans, and artisans use techniques such as painting, carving, sculpting, and modeling to create more diverse shapes. With the support of techniques such as kiln transformation, mud painting, enamel decoration, and relief, earthenware is no longer a simple combination of mud and fire. In particular, the refinement of earthenware products through glazing and painting on their surfaces has become one of the effective ways for the industry to target young people. However, most coatings contain various harmful substances. Therefore, direct crushing and recycling of earthenware waste will lead to the radioactive spread of harmful substances in the coatings the organic coatings on the surface of earthenware, enzymes secreted by microorganisms decompose their organic small molecules into small-molecule organic substances. For degradable glazes, composite microbial communities can be used for degradation to reduce the bonding force between the glaze and the earthenware matrix, which is conducive to subsequent separation and recovery and provides basic conditions for the reuse of the substrate.

The earthenware waste is crushed into uniform particles and put into compost raw materials in proportion. The ceramsite particles construct a three-dimensional pore structure inside the compost pile, improving the air permeability of the pile. Moreover, the chemical inertness of ceramsite can avoid the reaction of nutrients such as nitrogen and phosphorus in the compost, reducing nutrient loss. After composting, the ceramsite can be screened and recovered for repeated use in composting. The earthenware waste is ground to more than 100 meshes, activated by sodium hydroxide solution, and loaded with microorganisms with adsorption function to produce biological adsorption materials. This material has good adsorption performance for heavy metal substances in wastewater. The prepared composite material has a saturated adsorption capacity for hexavalent chromium in electroplating wastewater, and the adsorption rate can reach 97% under pH 3.0 conditions. Adsorption mechanism research shows that the anorthite phase in ceramsite can provide coordination sites and form synergistic adsorption centers with carboxyl and phosphate groups in microbial extracellular polymers. After adsorption saturation, heavy metals are recovered by acid washing and desorption, and the earthenware industry constructs a low-cost wastewater treatment system in this way.

4.4 Advanced Treatment Processes

At present, scholars at home and abroad have developed a variety of new sintering technologies, such as microwave sintering, plasma sintering, flash sintering, and liquid-phase sintering, trying to achieve ceramic densification at a lower temperature by introducing external pressure, electric field, or adding a liquid phase. In terms of reducing the sintering temperature, the earthenware industry can learn from these processes to achieve the purpose of reducing energy consumption.

Through low-temperature sintering regeneration technology, the sintering temperature of the regenerated green body from earthenware waste is reduced, reducing the energy consumption per unit product. The sintering temperature of the regenerated green body from earthenware waste is reduced to about 75% of the temperature used in traditional processes, which will reduce carbon dioxide emissions and energy consumption. Alternatively, through the non-firing process, natural solidification is used instead of sintering to further reduce waste gas emissions and minimize energy consumption.

The earthenware waste residue is ground into fine powder, mixed with raw earthenware in proportion, and a small amount of thickener is added to make printing slurry with matching fluidity and thixotropy. Using melt deposition molding or photo polymerization molding technology, through numerical control equipment, layer-by-layer printing is carried out to custom-produce green bodies such as artistic earthenware structures or small building decoration objects, which are then sent to the drying kiln.

5 Challenges Faced by Green and Environmental Protection Issues

5.1 Technical Bottleneck: The Discontinuity between Tradition and Modernity Restricts Upgrading

China is a major country in earthenware production. Taking Yunnan purple pottery as an example, making pottery generally involves selecting a certain amount of clay and then going through processes such as clay preparation, forming, decoration, and firing. The procedures are time-consuming and labor-intensive, and the labor cost is extremely high. Moreover, kiln firing is the most important procedure that determines whether each earthenware piece is successful and its value. In addition, kiln transformation firing has relatively high risks. Its success is closely related to the weather of the day and directly linked to the potter. If the potter is in good spirits, has a healthy mindset, rich experience, and extraordinary courage, the probability of kiln transformation is higher, and the effect of kiln transformation is better. On the contrary, there will be no kiln transformation, and even a whole kiln of pottery blanks may be burned and wasted. It relies heavily on the burner's experience in controlling temperature and humidity. However, these experiences do not have a scientific and systematic firing principle, but are only based on the experience passed down from generation to generation by handicraftsmen.

At the same time, the traditional wood-firing process will consume a large amount of wood raw materials and emit a large amount of waste gases such as carbon dioxide and carbon monoxide, which is inconsistent with the national measures to implement a low-carbon economy. Although some regions use electric furnace firing and digital detection supported by high technology, for example, Rong County earthenware integrates modern technology into earthenware production, and the qualified rate is as high as 95%. However, the overall penetration rate of using technology to produce earthenware is relatively low. Most regions' earthenware production is in small workshops, and a complete production system has not been formed. Due to cost factors, high technologies such as low-temperature firing have not been successfully promoted, and the raw material utilization rate is only about 65%. Compared with the international advanced level, China still has an obvious gap in the field of high-value utilization of waste. The Savona Ceramic District in Italy converts ceramic slag into porous ceramic membranes through plasma-assisted sintering technology, with a porosity of 65±3% and a compressive strength of 28MPa, which has been applied to Milan's urban drainage system; the Tokoname ware production area in Japan has developed a ceramic powder-resin composite injection molding process, enabling waste ceramic materials to replace 40% of the materials in automotive interior parts. In contrast, although China's utilization rate in the field of basic building materials reaches 75%, the industrial application in the above high-tech and high-value-added fields is still less than 5%. This structural gap indicates that it is urgent to establish an interdisciplinary R&D platform, introduce materials genome technology into the traditional ceramic industry, and predict waste modification paths through computational materials science to break through the technical bottleneck of industrial upgrading.

5.2 Economic Restriction: The Imbalance between Cost and Benefit Suppresses Development

In the traditional firing process, the labor costs associated with mining, ore drying, clay preparation, bottoming, blank stacking, cap making, blank hammering, capping, drying, glazing, firing, and kiln discharge, combined with the expense of externally purchased glazes and fuel, make the production costs of earthenware products extremely high. If automated high technologies are introduced to treat earthenware waste on this basis, small and medium-sized enterprises and small workshops everywhere will find it difficult to bear such high costs. In addition, traditional earthenware products are mostly daily-use items with low added value, such as flower pots and wine jars. For example, the output value of Rong County earthenware industry exceeded one billion yuan in 2020, among which wine jars have accounted for more than 30% of the domestic market share, and civilian pickled vegetable jars have accounted for about 15% of the national market share. Although earthenware culture receives support from tourism and government policies, the brand awareness and cultural communication degree of earthenware are still relatively low. High-value-added earthenware products are expensive and have limited uses, so the audience for such earthenware products is small. It can be seen that earthenware has high costs but low benefits and meager profits. Even though most regions try to centralize and intelligentize the earthenware industry, China's earthenware industry lacks a complete and mature cost control system, unable to form a scale effect, which further leads to the compression of earthenware products' profits and the inability to invest more funds into waste disposal technologies.

5.3 Lack of Policies and Standards: Institutional Shortcomings in Industry Development

At present, the earthenware industry lacks national unified standards in terms of raw material selection, craftsmanship, and quality inspection. Most regions produce earthenware products using traditional craftsmanship, which relies heavily on the burner's experience and judgment, affecting the quality standards of earthenware products. As a result, earthenware products on the market are uneven, reducing consumers' trust and having a certain negative impact on brand building. The structural imbalance in policy support also deserves attention. Although the Revitalization Plan for Traditional Crafts has included 15 categories of earthenware techniques in the protection list, in the national intangible cultural heritage protection fund in 2022, investment in the digital inheritance of earthenware techniques accounted for only 23% of the total ceramic sector. Meanwhile, for special subsidies for environmental protection renovation of kilns, the application success rate of earthenware enterprises was less than one-third that of large-scale ceramic enterprises. In ceramic production areas such as Chaozhou in Guangdong and Dehua in Fujian, enterprises could enjoy a 30% purchase subsidy for desulfurization and dust removal equipment; however, earthenware workshops in the same regions basically failed to obtain corresponding support due to failing to meet the threshold of "annual tax payment of more than 500,000 yuan" specified in the Measures for the Administration of Subsidies for Environmental Protection Equipment. This policy gap has led to lagging progress in environmental protection and renovation of the earthenware industry. Monitoring data shows that the PM2.5 emission concentration in traditional production areas still reaches 32 μg/m³, 41% higher than that in modern ceramic industrial parks.

In terms of industrial integrated development, although the Ministry of Culture and Tourism has launched the "Intangible Cultural Heritage Enters Daily Life" plan, there are still institutional gaps in key links targeting the earthenware industry, such as e-commerce live streaming norms and cultural tourism product development. The Longquan celadon industry in Zhejiang has achieved a 470% growth in e-commerce sales in three years through the model of "live streaming base certification + product traceability insurance"; in contrast, due to the lack of a quality guarantee mechanism for live-streamed commodities, the online sales proportion of Rongchang earthenware in Chongqing has remained around 15% during the same period. More notably, currently, only a few regions in China, such as Jianshui in Yunnan, have established earthenware cultural heritage transformation funds. Through the model of "design subsidies + channel connection", the fund has enabled the premium rate of local earthenware products in the cultural and creative market to reach 150%. However, due to the lack of similar mechanisms in most production areas, the growth rate of product added value has been lower than 8% for five consecutive years. This insufficient institutional supply not only restricts the transformation of the market value of traditional crafts, but also leads to the continuous weakening of internal motivation for industrial upgrading, forming a circular dilemma of "lack of standards—unstable quality—policy neglect—lagging development".

6 Countermeasures and Suggestions for Earthenware Waste Disposal

6.1 Develop High-efficiency and Low-energy-consumption Resource Utilization Technology

The pottery industry can purchase highly intelligent equipment. For example, Shunfa Pottery Industry in Rong County invested 160 million yuan in a technology-driven project to establish a new type of pulse environmental protection tunnel production line. The fully automatic temperature-controlled tunnel kiln reduces energy consumption by more than 30% compared with ordinary kilns. In addition, some tunnels adopt an intelligent temperature control system and waste heat recovery system, further reducing energy consumption and carbon emissions.

For the waste mud generated during earthenware production, enterprises can optimize production steps, precisely control the amount of water added to the clay and the stirring duration, stabilize the internal structure of the green body, enhance the plasticity of the mud, and reduce the rate of defective products, thereby lowering energy consumption during the waste crushing process. The waste mud and waste embryos after sorting, slurry, iron removal, and screening can be directly mixed into the large-scale production slurry for use. Those with more impurities can be used to make the body pads for firing. For waste glaze, after strict sorting and re-grinding, additives are added, then iron removal and screening are carried out. After being fired, they are mixed into the large-scale production glaze in proportion. For waste glaze with more impurities, it can be used as the glaze for the glazing of water closet pipelines.

Drawing on the production principle of ERC new materials, break the traditional landfill treatment method of earthenware waste, and develop environmental protection new material preparation technology with earthenware waste as the core. By controlling the temperature during the firing process, heat insulation materials with good combustion performance and low water absorption are fired for the infrastructure industry, adapting to the national low-carbon economy goal. At the same time, earthenware waste can be broken and reprocessed to form mosaic decorative materials, further expanding the industrial chain of earthenware and increasing its added value.

6.2 Earthenware Waste Recycling and Green Supply Chain Construction

Optimize the earthenware waste disposal structure and form a complete, classified recycling system. For wastes such as "waste mud, waste embryos, waste finished products, and waste glaze" generated respectively in the production process, collect them in detail take corresponding measures for treatment, and clarify the recycling standards and temporary storage requirements for different types of wastes. For the recycling system, a recycling network with "enterprises as the center, government as the guide, and society as the participant" can also be constructed. Establish recycling points in concentrated areas of the earthenware industry, set up small recycling points in communities or small workshop areas, and establish online recycling points through various social platforms to solve the problem that scattered wastes are difficult to collect and treat centrally. It is estimated that for a sanitary ware enterprise with an annual output of 1 million pieces, for every 1% increase in the amount of waste porcelain powder added to the mud formula, more than 200 tons of waste porcelain can be consumed every year, increasing benefits by 250,000 yuan. When promoted to the entire industry, the benefits are more considerable.

In addition, the government should set up a special fund for earthenware waste disposal to support and encourage earthenware enterprises or individuals to actively dispose of waste and improve the enthusiasm of the recycling network chain. Regarding green supply chain management, it is a way for enterprises to fulfill their social responsibilities and an inevitable path to embrace the new era of ecological civilization and green economic development. Through this management, resource allocation is optimized, the demand and supply of raw materials for earthenware production are accurately matched, the waste of excessive raw material procurement is reduced, and the market demand for environmentally friendly products is met. This helps to build a green brand image of earthenware products and enhance their competitiveness in policy support and the market.

6.3 Improve Relevant Laws, Regulations and Standards

Draw on the standard rules of the Emission Standard of Air Pollutants for the Ceramic Industry to formulate local standards for earthenware production in various regions, such as the classification guidelines for earthenware waste and the quality standards for resource and energy recovery of waste. Clarify the key indicators for the particle size of regenerated waste and standardize the recycling and utilization process. The government shall clarify the responsibilities and obligations of earthenware enterprises under the "dual carbon" goals and their responsibility for the "harmless treatment" of earthenware waste recycling and disposal through legislation. Establish a complete legal supervision system covering generation, recycling and utilization. Incorporate the proportion of waste resource reuse into the environmental protection assessment of each enterprise, and increase the punishment for enterprises that directly discard or bury waste.

Establish an innovative mechanism of tri-database linkage and set up a special R&D fund, focusing on supporting key technological breakthroughs such as low-temperature sintering aid development. Simultaneously, establish a hierarchical certification system for green ceramic products.

To address issues such as high costs and low income in the earthenware industry, the government should introduce relevant preferential tax policies and special subsidy benefits. Implement tax exemptions or partial value-added tax reductions for enterprises that reuse earthenware waste as resources. Provide financial subsidies to enterprises in the processes of mud excavation, extraction and washing to reduce labor costs and financial pressure. At the same time, establish green credit channels, give priority to encouraging project financing for enterprises engaged in waste resource utilization, and increase financial support for green and environmental protection technologies. This will reduce the cost of industrial transformation and upgrading, and promote the green development of the earthenware industry in waste disposal.

7 Conclusion

China is a major producer and exporter of earthenware. In recent years, earthenware has been mainly protected as an intangible cultural heritage, but there are still various problems in the economic development of its enterprises. With the development of the industry, the disposal of earthenware waste has become one of the urgent problems to be solved in this industry. From raw material mining to firing finished products, and then to the use and waste stage of earthenware, it shows the damage to the environment and waste of resources caused by waste in different processes. By analyzing data from different aspects, such as the qualified rate of earthenware enterprises and waste disposal technologies, the study has understood the development status of China's earthenware industry in recent years, as well as the various problems existing in waste disposal, and put forward corresponding countermeasures and suggestions to promote the sustainable development of China's earthenware industry and realize a circular economy.

There are many problems in the green and environmental protection technologies for earthenware waste disposal. China's earthenware is far below the international advanced level in technologies such as waste recycling. With the development of the green economy and the national "dual carbon" goals, the national standards for earthenware waste disposal are getting higher and higher. Traditional crafts are inefficient, and modern crafts are insufficiently penetrated. The process of firing earthenware with firewood is cumbersome, and it relies heavily on the burner's experience in controlling the firing temperature. The fuel for firewood firing also releases a large amount of waste gas. The technology penetration rate in most regions is low, and the functional technologies for waste reuse are difficult to implement. The production cost of earthenware is high, and the sales revenue is low. The cumbersome process means high labor and raw material costs, high pricing, and a small target customer group, resulting in low income. If green and environmental protection technologies for waste disposal are added, the earthenware industry will face a situation of operating at a loss. China's standard system for the earthenware industry is not unified, and the precision support is insufficient. The non-uniform waste recycling standards and the lack of special fund support will all hinder the development of the earthenware industry and the green disposal of waste.

In response to a series of problems in the green disposal of waste in the earthenware industry, corresponding countermeasures are proposed. Developing high-efficiency and low-energy-consumption resource utilization technologies can improve the qualified rate of earthenware and reduce energy consumption. Establishing a recycling system for earthenware waste and clarifying recycling standards. Establishing recycling points corresponding to earthenware enterprises of different scales can solve the problem of scattered waste recycling. Improving relevant laws and strengthening government policy support can increase the utilization rate of waste resources and enhance the enthusiasm of earthenware enterprises in the green disposal of waste. Through these countermeasures and suggestions, the development of China's earthenware industry can be promoted. Relevant enterprises will develop from being numerous but small to being fewer but stronger, increasing economic income, and promoting the modernization, technological transformation development of the earthenware industry.

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