

An Upgraded Technological Pathway for Urban Sludge Management under China's Dual Carbon Goals: A Case Study of Advanced Ultra-High Pressure Belt Filter Press Technology

Lijuan Xie¹, Tao Chen^{1,*}, Weizhen Fan¹, Guihua Li¹

¹Tai'an City Urban Management Comprehensive Service Center, Tai'an, China

Abstract: China's "Dual Carbon" initiative necessitates a green transformation in urban sludge management, where conventional dewatering is hindered by high residual moisture and energy consumption, severely limiting volume reduction and resource recovery. This paper investigates an upgraded technological pathway centered on the Advanced Ultra-High Pressure (A-UHP) belt filter press. The A-UHP technology reduces sludge moisture from a conventional 70-80% to below 40%, achieving significant source reduction, while an integrated PLC system optimizes operational efficiency by minimizing energy and chemical inputs. This deep dewatering process enhances the cake's calorific value, enabling its valorization as a fuel for incineration, a feedstock for cement kilns, or a component in construction materials. This establishes a new management paradigm of "source reduction—process optimization—resource empowerment." A comprehensive assessment confirms the pathway's significant economic, environmental, and social benefits, highlighting its potential for synergistic pollution and carbon reduction. The paper concludes by analyzing implementation challenges and proposing policy recommendations to guide the high-quality development of sludge management in China.

Keywords: Dual Carbon Goal, Sludge Management, Deep Dewatering, Resource Recovery, Pollution and Carbon Reduction

1. Introduction

The pursuit of China's "Dual Carbon" goals—achieving peak carbon emissions before 2030 and carbon neutrality before 2060—has imposed elevated demands for technological innovation within the nation's environmental protection sector. National leadership has repeatedly emphasized that scientific and technological advancement serves as the core driver of societal progress, charting a clear course for the high-quality development of ecological and environmental protection. Within this context, the management of municipal sludge, a critical link in urban aquatic ecosystem governance, confronts a new set of challenges and opportunities. National strategic documents, including the "14th Five-Year Plan," have set explicit targets, stipulating that the harmless disposal rate of urban sludge must exceed 90% by 2025, with a long-term vision for 2035 that includes the comprehensive realization of harmless disposal and a marked increase in resource utilization[1]. Concurrently, the *Implementation Plan for Promoting Equipment Renewal in the Industrial Sector* mandates a greater than 25% increase in industrial equipment investment by 2027 compared to 2023 levels, advocating for a comprehensive push towards digital transformation and the adoption of advanced machinery[2]. These policy directives provide powerful support for the technological upgrading and equipment innovation required in the field of sludge management.

At present, sludge dewatering equipment is central to the objectives of sludge volume reduction and stabilization. However, conventional technologies such as traditional belt filter presses and centrifugal dewatering machines are beset by persistent issues. These include high residual moisture content in the final sludge cake (typically remaining between 60% and 80%), substantial consumption of chemical conditioners, high energy demands, and insufficient operational stability. The persistently high moisture content of sludge poses a dual challenge. Logistically, it inflates the costs associated with transportation and subsequent disposal. From a sustainability perspective, it severely constrains the potential for resource recovery and undermines the realization of carbon reduction benefits, creating a significant bottleneck in the circular economy pathway for wastewater treatment residuals. Consequently, there is an urgent imperative to explore and establish an upgraded technological pathway for sludge management,

guided by the principles of the “Dual Carbon” agenda. This paper utilizes the Advanced Ultra-High Pressure belt filter press as a case study to investigate how its advanced deep dewatering capabilities can overcome the limitations of traditional methods. It aims to delineate a synergistic pathway that integrates sludge volume reduction, energy recovery, and resource utilization, thereby providing a theoretical analysis and practical framework for technological advancement in urban wastewater treatment plants.

2. Technological Advantages and Decarbonization Potential of the Advanced Ultra-High Pressure Belt Filter Press

In response to the aforementioned challenges, a new generation of innovative technologies designed to overcome the bottlenecks of conventional sludge management has emerged, with the Advanced Ultra-High Pressure belt filter press standing out as a representative achievement. Developed by Taian Qingyuan Water Co., this novel deep dewatering machine was granted a national invention patent by the China National Intellectual Property Administration in 2021 (Patent No. CN 113045170 A). The theoretical underpinnings of its technology have been articulated in the peer-reviewed *China Science and Technology Industry* journal, establishing a solid foundation for its technical sophistication and reliability[3]. The core breakthrough of this equipment lies in its fundamental resolution of the chronic problems plaguing traditional dewatering machines, namely low efficiency, high residual moisture content (typically above 60%), and operational instability. By achieving highly efficient sludge volume reduction at the front end of the disposal chain, it creates a transformative impact. The subsequent sections will provide a detailed analysis of how this technology constructs a pioneering pathway for sludge management, examined through the three interconnected dimensions of its source reduction benefits, its efficiency gains from intelligent control, and its enhancement of resource recovery potential.

2.1 Source Reduction via Advanced Dewatering

The primary advantage of the Advanced Ultra-High Pressure belt filter press lies in its capacity for profound source reduction, achieved by mechanically dewatering sludge to an unprecedented degree. The technology integrates traditional belt filtration with a high-pressure diaphragm squeezing stage. Operating at mechanical pressures exceeding 2 MPa, this system executes an intensified compression sequence that expels not only free and interstitial water but also a significant portion of the bound water within the sludge matrix. This process results in a remarkable reduction in the final sludge cake's moisture content, lowering it from a typical baseline of over 70% to approximately 40%[4].

This dewatering efficacy directly translates into a doubling of the sludge's solid content, from approximately 30% to as high as 60%. The direct physical consequence is a reduction in the total weight and volume of the final sludge cake by approximately 50%. This substantial volume contraction yields immediate logistical and environmental benefits, primarily through decreased fuel consumption and associated carbon emissions during transport and handling.

Furthermore, the reduction in moisture critically enhances the sludge's energetic properties. The net calorific value (NCV) of the sludge cake is substantially increased. Whereas conventional sludge (>70% moisture) is an energy sink requiring auxiliary fuels for incineration, the dewatered cake (≈40% moisture) approaches the threshold for autogenous combustion (the energy break-even point). This effectively transforms the sludge from a disposal liability into a viable, high-calorific feedstock for waste-to-energy processes. Thus, through advanced mechanical dewatering alone, this technology achieves the dual objectives of curtailing final disposal volumes and creating a value-added product, fundamentally minimizing the environmental and economic burden of sludge management.

2.2 Enhanced Efficiency through Intelligent Process Control

A pivotal feature of the Advanced Ultra-High Pressure system is its integration of a Programmable Logic Controller (PLC), which introduces a layer of intelligent automation to optimize the dewatering process[5]. The PLC system continuously monitors real-time variations in sludge characteristics and operating conditions, automatically adjusting key parameters such as sludge feed rate, chemical dosage, and compression pressure to ensure the unit consistently operates at peak performance. This intelligent control mechanistically enhances dewatering efficiency while concurrently reducing energy and chemical consumption, preventing the waste associated with manual inaccuracies like flocculant overdosing or inefficient, non-steady-state operation.

In contrast to conventional processes that rely on operator experience, the PLC system utilizes data

from online sensors—monitoring metrics like cake moisture and slurry viscosity—to dynamically adjust the frequency of dosing pumps and drive motors. This ensures that flocculation and filtration consistently occur within the most efficient range. This optimization not only curtails chemical consumption by over 20% but also improves the stability of the cake's solid content and the overall production rate.

Furthermore, the automated control system enables one-touch startup/shutdown and unattended operation, minimizing human error and enhancing operational safety. Case studies have demonstrated that PLC-equipped machines exhibit lower failure rates, reduced maintenance costs, and approximately 10-20% lower overall energy consumption than traditional equipment, all while guaranteeing stable performance. The convergence of digital and automated technologies thus provides a powerful foundation for improving efficiency and reducing consumption, aligning with the broader trends of industrial digital transformation and the pressing needs of the wastewater treatment sector.

2.3 Amplifying Potential for End-of-Pipe Resource Recovery

The substantial moisture reduction achieved by the Advanced Ultra-High Pressure dewatering machine renders the resulting sludge cake significantly more amenable to resource recovery. This contrasts sharply with traditional high-moisture sludge (70-80%), whose low net energy and high processing costs limit its value and necessitate an additional, energy-intensive thermal drying stage. The sludge cake produced by the advanced process, with a moisture content of approximately 40%, possesses a markedly higher calorific value, allowing its direct utilization as a fuel or raw material in various downstream applications.

In the domain of energy recovery, this low-moisture sludge is an ideal feedstock for incineration-based power generation or for co-processing in cement kilns. At 40% moisture, its net calorific value approaches the thermal break-even point, enabling it to sustain combustion with minimal supplementary fuel and increasing thermal efficiency. When the moisture content drops below 25%, sludge incineration can generate a net energy surplus, transforming it into a valuable fuel resource. This allows for autogenous combustion in waste-to-energy facilities and creates the potential to export surplus energy, thereby displacing fossil fuels and generating tangible carbon reduction benefits.

From a material utilization perspective, the dry and stable nature of the 40%-moisture cake makes it suitable for processing into biomass fuel pellets or for manufacturing construction materials, such as ceramsite and bricks. The dewatering process also enhances the cake's stability and degree of sanitization by mitigating organic decomposition and eliminating a significant portion of pathogens, making it safer for transport and creating opportunities for its use as a soil conditioner. In summary, by dramatically increasing sludge dryness, this technology builds a crucial bridge to transform sludge from a "waste" to a "resource," substantially elevating its potential for downstream energy and material recovery and positioning it as a standout solution under the "Dual Carbon" framework.

3. A New Paradigm for Sludge Management: Pathway Construction and Comprehensive Benefit Analysis

3.1 Framework for an Upgraded Management Pathway

Building upon the detailed technological advantages, an upgraded pathway for urban sludge management can be constructed that aligns with the "Dual Carbon" agenda. This constitutes a paradigm shift from the traditional model of "conventional dewatering + landfilling/incineration" to a more sustainable "Advanced Ultra-High Pressure dewatering + diversified resource recovery." The conventional pathway produces a high-moisture cake (70-80%) with limited volume reduction. Subsequent disposal through landfilling consumes valuable land and carries risks of leachate and greenhouse gas emissions, while incineration is energy-intensive and inefficient for such wet material.

The upgraded pathway, in contrast, positions the Advanced Ultra-High Pressure dewatering machine as its core unit, drastically reducing moisture content to 40% or lower at the front end of the system. This pre-treated sludge cake can then be channeled into various resource recovery streams. For example, it can be used for energy generation through direct incineration or as a substitute fuel in cement kilns, with the resulting ash being repurposed for construction materials. Furthermore, after appropriate stabilization, the deeply dewatered sludge can be utilized in agriculture and landscaping as a component of organic fertilizers[6].

This upgraded pathway transforms the sludge management system from a model of "insufficient

reduction leading to a downstream burden” to a new model of “comprehensive frontend reduction enabling downstream resource recovery.” Its central tenet is using advanced equipment to lower moisture content, thereby unlocking the sludge's residual value for synergistic benefits in pollution and carbon reduction. This approach aligns with national development plans promoting resource recovery. As this pathway is adopted, it will establish a new operational standard, but its effective implementation requires a supportive ecosystem of standards and regulations for both the dewatered products and the associated processes.

3.2 Economic Viability and Cost-Benefit Analysis

The sludge management pathway centered on Advanced Ultra-High Pressure dewatering offers significant multifaceted economic advantages. Primarily, the reduction in sludge moisture directly translates to lower disposal costs. Project data indicates that reducing sludge moisture from 80% to 60% halves its weight, cutting disposal fees by approximately 200 RMB per ton. For a medium-sized wastewater treatment plant, this can culminate in annual savings of up to 2.19 million RMB. Such substantial savings suggest a rapid return on investment, confirming the technology's economic feasibility.

Secondly, the pathway leads to a marked reduction in overall operational costs. Although the initial capital outlay for the Advanced Ultra-High Pressure unit is higher, it generates considerable cost savings in downstream processes. The dramatic reduction in sludge mass directly lowers transportation costs by over 50% and curtails the energy required for subsequent thermal drying by approximately 40%. When coupled with the efficiencies gained from the intelligent control system, the total operational expenditure is markedly lower than that of traditional processes.

Finally, this pathway unlocks potential revenue from resource recovery by transforming sludge from a negative-value waste into a resource with tangible value. Its application as a fuel in energy recovery processes or as a raw material in cement and brick production can offset energy costs and reduce the need for virgin materials. In conclusion, the pathway's economic superiority stems from its tripartite benefits: reduced disposal fees, lower operational costs, and new resource valorization opportunities. Its full lifecycle economic performance surpasses traditional models, with the future potential for enhanced returns through the monetization of carbon assets via mechanisms like carbon trading.

3.3 Environmental Impact Assessment and Carbon Footprint Reduction

The environmental benefits delivered by this upgraded sludge management pathway are extensive and profound. A primary outcome is a significant reduction in pollution. By implementing deep dewatering at the source, the volume of sludge requiring final disposal is drastically curtailed. This fundamentally alleviates the environmental pressures on landfills, including the generation of leachate, the emission of greenhouse gases like methane, and the release of noxious odors. Uncontrolled landfilling of organic sludge is a major source of methane, a potent greenhouse gas, making it a critical area for emissions reduction. By diverting sludge to an efficient dewatering and resource recovery route, the anaerobic decomposition that produces these fugitive emissions is effectively prevented, thereby mitigating the risk of non-point source pollution. It is estimated that, compared to landfilling, a sludge management route involving incineration and co-processing can reduce methane and other greenhouse gas emissions by over 80%.

A second major benefit is a substantial reduction in the carbon footprint. The new pathway achieves this through multi-faceted energy optimization and recovery. The halving of sludge transport volume directly reduces fuel consumption and vehicle exhaust emissions. More significantly, the ability of the dewatered sludge to support autogenous combustion and facilitate waste heat recovery drastically decreases the reliance on fossil fuels. One project that implemented a "filter press + low-temperature drying + co-incineration for power generation" process reported a nearly 50% reduction in its total carbon footprint compared to the traditional "mechanical dewatering + direct incineration" route. Furthermore, the energy generated from incinerating one ton of sludge was sufficient to offset approximately one ton of CO₂ equivalent emissions from the process itself.

Moreover, the "carbon compensation" effect achieved by valorizing sludge as a resource is a critical factor. Utilizing the calorific value of sludge for energy generation directly displaces an equivalent amount of fossil fuel combustion, which can be accounted for as a negative emission. Research calculating the full heat and power co-generation potential of sludge co-combustion found that the carbon offset could reach approximately -0.2 tons of CO₂ equivalent per ton of sludge, highlighting the proactive role of sludge resource recovery in the journey toward carbon neutrality. Finally, the pathway delivers

broader ecological benefits. Efficient sludge reduction and safe resource recovery minimize the demand for land, reduce the long-term risks of soil and groundwater contamination from sludge stockpiles, and improve urban environmental sanitation and public satisfaction. From a wider perspective, this upgraded pathway promotes a circular economy by facilitating pollutant recycling and energy recovery, aligning perfectly with the principles of sustainable and low-carbon urban development. In essence, the sludge management model driven by Advanced Ultra-High Pressure dewatering demonstrates pronounced advantages in both reducing pollution and shrinking the carbon footprint, representing an effective and practical application of synergistic environmental management.

3.4 Socio-Managerial Benefits and Industrial Advancement

The implementation of this upgraded technological pathway for sludge management also yields significant social and managerial benefits. On one hand, the adoption of such new technologies stimulates the advancement of the environmental protection industry. The research, development, and manufacturing of high-end equipment like the Advanced Ultra-High Pressure sludge dewatering machine catalyze progress in related sectors, including mechanical engineering, hydraulics, and automated control systems. This fosters the domestic production of advanced environmental equipment, promotes technological self-sufficiency, and cultivates new points of economic growth. On the other hand, the enhancement of harmless sludge disposal and resource recovery directly addresses public concerns regarding environmental quality and resource circularity. This elevates social satisfaction with environmental governance and strengthens public trust in municipal services.

At the policy level, this pathway provides robust support for achieving the goals outlined in national planning documents, such as the *"14th Five-Year" Development Plan for Urban Wastewater Treatment and Resource Utilization*, serving as a replicable model for localities aiming to comprehensively upgrade their sludge management capabilities. Furthermore, technological advancement is intrinsically linked with improvements in specialized operational capacity and intelligent supervision, which helps transform industry management models. Through the use of automation and information technology, it becomes possible to achieve real-time monitoring and data analysis across the entire sludge treatment process. This empowers regulatory authorities to more effectively oversee facility operations and assess performance against emission reduction targets, a practice consistent with national advocacy for "smart environmental protection" and professionalized operations and maintenance. Additionally, the promotion and application of sludge-derived products, such as construction materials and soil amendments, hold the potential to create new jobs and market demand, fostering a virtuous cycle of mutual reinforcement between environmental protection and economic development. In sum, the comprehensive environmental, economic, and social benefits generated by this technological pathway demonstrate that it is more than a mere engineering improvement; it is a vital strategic measure for propelling the entire field of urban sludge management toward high-quality, sustainable development.

4. Implementation Challenges and Policy Recommendations

4.1 Key Implementation Challenges

Despite its demonstrable superiority, the large-scale implementation of Advanced Ultra-High Pressure sludge dewatering technology faces several practical challenges. Key among these are high initial capital investment and lifecycle costs, including energy consumption and replacement parts, which pose a significant barrier for smaller, capital-constrained wastewater treatment plants. A second challenge is the lack of systemic integration with downstream resource recovery outlets. Without established channels like incinerators or cement kilns, the full benefits of the advanced treatment are negated, creating logistical bottlenecks and risking the production of a high-value intermediate product with no viable end-market. Further hurdles include operational complexities that demand advanced training for personnel, a significant regulatory gap in quality and safety standards for sludge-derived products, and public perception barriers regarding the use of these materials, which collectively hinder broad market acceptance and commercialization.

4.2 Policy Recommendations for Promoting Adoption

To address these challenges, targeted policy support is essential. It is crucial to establish robust financial support mechanisms, such as subsidies and performance-based incentives, to de-risk initial investments and alleviate the financial burden on plant operators. Concurrently, the development of a

comprehensive system of technical and product standards is urgently needed for both the dewatering equipment and the resulting sludge-derived materials to provide clear quality benchmarks, ensure safety, and facilitate market acceptance. Strategic government action should also focus on the coordinated planning of regional resource recovery facilities to create stable end-markets for the dewatered product. Finally, successful adoption hinges on enhancing human and social capital through specialized personnel training and transparent public education campaigns. Promoting integrated pilot projects will also be critical to demonstrating technological viability, validating economic models, and achieving economies of scale through regional cooperation.

5. Conclusion and Future Outlook

This paper has examined an upgraded technological pathway for urban sludge management, focusing on the Advanced Ultra-High Pressure belt filter press. The research confirms that this technology can reduce sludge moisture content to below 40%, leading to significant reductions in volume, disposal costs, and carbon emissions. By integrating intelligent controls and enabling diverse resource recovery options, it effectively transforms sludge from a pollutant into a resource. This new paradigm—"efficient source reduction—intelligent process optimization—end-of-pipe resource empowerment"—is not only economically viable but also substantially reduces environmental risks, offering a new blueprint for the high-quality development of the sector.

The large-scale implementation of this technology, however, requires robust support through conducive policies, clear standards, and effective management. Further efforts must be made to bridge the gap between research and practice through multi-regional pilot projects. Looking ahead, sludge management technology will continue to evolve toward the goals of reduction, sanitization, resource recovery, and intelligence. The innovative practice embodied by the Advanced Ultra-High Pressure belt filter press provides an invaluable paradigm for this trajectory. With continued advancements, deep dewatering equipment is expected to achieve even higher efficiency and broader applicability, providing a solid technological foundation for the green, low-carbon, and circular management of urban sludge in China and contributing to the ultimate realization of carbon neutrality.

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