

## Review Article

# Sustainable Wastewater Management and Resource Recovery Opportunities in Biomass Power Plants

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### ABSTRACT

Biomass-based power generation is widely recognized as a renewable alternative to fossil-fuel energy systems. However, biomass power plants generate wastewater streams containing suspended solids, organic compounds, dissolved salts, and trace metals from processes such as boiler blowdown, cooling tower operation, ash handling systems, and flue gas cleaning units. Improper management of these effluents may result in environmental contamination and inefficient water utilization. Conventional wastewater treatment methods typically focus on pollutant removal for regulatory compliance, often neglecting opportunities for water reuse and resource recovery. This study presents a conceptual framework for sustainable wastewater management in biomass power plants through an integrated review of treatment technologies and resource recovery strategies. A systematic analysis of recent literature was conducted to identify key technological developments in industrial wastewater treatment, including biological processes, membrane technologies, electrochemical treatment, and advanced oxidation processes. The study further examines opportunities for recovering water, nutrients, and energy from wastewater streams generated in biomass energy systems. Based on the literature synthesis, a sustainable wastewater management framework is proposed that integrates conventional and advanced treatment technologies with resource recovery pathways. The framework emphasizes wastewater segregation, multi-stage treatment processes, and circular water reuse within biomass power plant operations. The findings highlight that adopting integrated wastewater management strategies can significantly reduce environmental impacts while improving operational sustainability in biomass energy production. The proposed framework contributes to advancing circular economy approaches in renewable energy infrastructure and supports the transformation of wastewater treatment systems into resource recovery facilities.

### KEYWORDS

*Biomass power plants, Industrial wastewater treatment, Resource recovery, Circular economy, Sustainable water management, Advanced wastewater treatment*

## I. INTRODUCTION

The global transition toward sustainable energy systems has intensified research and investment in renewable energy technologies. Among these technologies, biomass-based power generation has emerged as an important component of renewable energy portfolios due to its ability to utilize organic residues such as agricultural waste, forestry residues, and industrial by-products [1].

Biomass energy systems contribute to waste management while reducing dependence on fossil fuels and mitigating greenhouse gas emissions.

Despite these environmental advantages, biomass power plants generate various forms of industrial wastewater during routine operations. Wastewater streams arise from several process units including boiler blowdown systems, cooling towers, ash handling facilities, and flue gas treatment operations. These wastewater streams may contain a complex mixture of suspended solids, dissolved salts, organic compounds, and trace metals that must be treated before discharge to prevent environmental pollution [2]. Industrial

wastewater management has historically focused on pollutant removal through conventional treatment technologies such as sedimentation, biological treatment, and chemical precipitation. While these approaches are effective for reducing contaminant concentrations, they often fail to address the broader sustainability potential associated with wastewater reuse and resource recovery [3].

Recent advances in environmental engineering have shifted attention toward integrated wastewater management strategies that treat wastewater as a resource rather than waste. Wastewater treatment facilities are increasingly being transformed into **water resource recovery facilities**, capable of recovering valuable resources such as energy, nutrients, and reusable water from industrial effluents. In this context, biomass power plants represent an important opportunity for implementing circular water management strategies. Wastewater generated during plant operations can potentially be treated and reused within the facility, reducing freshwater consumption and improving overall sustainability [4].

The objective of this study is to analyze wastewater treatment technologies applicable to biomass power plants and identify opportunities for integrating resource recovery into wastewater management systems. Through a systematic review of recent literature, the study proposes a sustainable framework for wastewater management that supports circular resource utilization in biomass energy systems.

## II. LITERATURE SURVEY

### 2.1 Industrial Wastewater and Sustainability Challenges

Industrial activities represent one of the most significant sources of wastewater generation worldwide.

Energy production facilities—including thermal and biomass power plants—produce complex wastewater streams containing organic matter, suspended solids, nutrients, dissolved salts, and heavy metals. Effective treatment of such effluents is necessary to protect aquatic ecosystems and comply with environmental regulations. In recent years, the concept of sustainable wastewater management has evolved beyond simple pollutant removal toward integrated resource recovery and circular economy frameworks. Modern wastewater treatment systems are increasingly viewed as water resource recovery facilities (WRRFs) capable of recovering valuable materials such as nutrients, energy, and reusable water from industrial effluents.

The adoption of circular approaches is driven by increasing water scarcity, stricter environmental regulations, and the need to reduce the environmental footprint of industrial operations. Research indicates that wastewater streams can contain recoverable resources including nutrients, metals, bioenergy substrates, and water suitable for reuse. In the context of energy systems, particularly biomass power plants, wastewater management presents both environmental challenges and opportunities for resource recovery. Biomass-based energy production involves multiple process stages, fuel preparation, combustion, cooling, and emissions control—which generate wastewater streams with diverse physicochemical characteristics [5].

### 2.2 Wastewater Generation in Biomass Power Plants

Biomass power plants produce wastewater through several operational processes including boiler blowdown, cooling tower operation, ash handling systems, and flue gas cleaning units. Each process contributes distinct pollutants to the wastewater stream. Boiler blowdown water typically contains high levels of dissolved salts, treatment chemicals, and corrosion inhibitors. Cooling tower blowdown water may contain scale inhibitors, anti-corrosion chemicals, and microbial control agents. Ash handling systems generate wastewater with high concentrations of suspended solids and trace metals, while flue gas desulfurization processes can produce acidic wastewater containing dissolved minerals and contaminants. Industrial wastewater composition varies depending on fuel type, combustion technology, and plant configuration. Agricultural biomass fuels may introduce additional organic compounds and mineral impurities into wastewater streams. Consequently, biomass power plant wastewater often requires multi-stage treatment approaches combining physical, chemical, and biological processes [6].

### 2.3 Conventional Wastewater Treatment Technologies

Traditional wastewater treatment systems rely primarily on **physical and biological processes** to remove suspended solids and biodegradable organic matter. Physical treatment processes typically include screening, sedimentation, and filtration to remove large particles and suspended solids. Chemical processes such as coagulation and flocculation are often applied to enhance particle aggregation and facilitate sedimentation.

Biological treatment processes, such as activated sludge systems, trickling filters, and aerated lagoons, are widely used to remove organic contaminants from wastewater. Recent studies have emphasized improvements in biological treatment technologies to enhance pollutant removal efficiency and operational stability. Activated sludge remains one of the most widely used biological treatment processes due to its ability to remove organic pollutants and nutrients effectively. However, conventional systems may face limitations including high energy consumption, sludge generation, and sensitivity to fluctuating wastewater composition [7].

### 2.4 Advanced Wastewater Treatment Technologies

To address the limitations of conventional treatment processes, researchers have developed several advanced technologies capable of removing recalcitrant pollutants and improving water reuse potential. Advanced oxidation processes (AOPs) utilize strong oxidizing agents such as hydroxyl radicals to degrade organic contaminants and micropollutants. Membrane technologies, including reverse osmosis, nanofiltration, and ultrafiltration, have also become increasingly popular for industrial wastewater treatment due to their high separation efficiency and ability to produce high-quality treated water suitable for reuse. Membrane bioreactors (MBRs) represent an important advancement in wastewater treatment technology. These systems combine biological treatment with membrane filtration, allowing higher biomass concentrations and improved pollutant removal performance compared with conventional biological processes. Electrochemical wastewater treatment technologies have also gained attention for their ability to remove contaminants with reduced sludge production and compact reactor designs. These systems utilize electrochemical reactions to degrade pollutants and precipitate dissolved metals from wastewater streams [8].

### 2.5 Resource Recovery from Wastewater

Resource recovery from wastewater has emerged as a key research area within sustainable environmental engineering. Instead of treating wastewater solely as waste, modern treatment approaches aim to recover valuable resources such as nutrients, energy, and reusable water. Energy recovery from wastewater sludge is commonly achieved through anaerobic digestion, which converts organic matter into biogas. Recent studies have also explored innovative technologies such as microbial fuel cells (MFCs) that simultaneously treat wastewater and generate electricity. Nutrient recovery is another important aspect of sustainable wastewater management. Nitrogen and phosphorus recovered from wastewater can be used as fertilizers, reducing reliance on synthetic chemical fertilizers and supporting circular nutrient cycles. Research on resource recovery has expanded significantly over the past decade,

reflecting growing interest in sustainable water management and circular economy principles. Bibliometric analyses indicate rapid growth in research publications related to biomass utilization and wastewater treatment technologies worldwide [9]. Overall, the transition from conventional wastewater treatment to resource recovery-based systems

represents a significant shift in environmental engineering practice. Sustainable wastewater management strategies are increasingly being adopted across industries to reduce water consumption, minimize environmental pollution, and support circular resource utilization.

References	Study Focus	Key Findings
[10]	Energy efficiency in wastewater plants	Highlighted integration of energy recovery and sustainability in treatment systems
[11]	Wastewater treatment technologies	Reviewed conventional and advanced technologies including AOPs and membranes
[12]	Industrial wastewater treatment	Identified major treatment techniques for different industries
[13]	Biological treatment technologies	Discussed advancements in integrated biological treatment systems
[14]	Sludge-to-energy technologies	Demonstrated feasibility of energy recovery from wastewater sludge
[15]	Sustainable wastewater management	Emphasized resource recovery and circular economy approaches
[16]	Membrane bioreactor technologies	Demonstrated improved treatment efficiency using MBR systems

### III. RESOURCE RECOVERY OPPORTUNITIES

In recent years, the concept of wastewater management has evolved from a pollution control approach to a resource-oriented perspective. Industrial wastewater, including that generated in biomass power plants, contains several recoverable components such as reusable water, nutrients, and energy-rich organic matter. Recovering these resources not only reduces environmental impacts but also contributes to improved operational efficiency and sustainability in energy production systems.

One of the most immediate opportunities for resource recovery in biomass power plants is the reuse of treated wastewater within plant operations. After appropriate treatment, wastewater can be reused in processes such as cooling tower makeup water, ash handling systems, equipment cleaning, and landscape irrigation. Implementing internal water reuse strategies reduces the demand for freshwater resources, which is particularly important in regions experiencing water scarcity or increasing industrial water competition.

Advanced treatment technologies such as membrane filtration and advanced oxidation processes can produce high-quality effluent that meets the standards required for industrial reuse applications.

In addition to water reuse, wastewater streams from biomass power plants may also contain nutrients such as nitrogen and phosphorus. These nutrients can potentially be recovered through processes such as chemical precipitation,

biological nutrient removal, or adsorption-based recovery systems. The recovered nutrients may be used as fertilizers or soil conditioners, contributing to circular nutrient management in agricultural systems. This approach aligns with circular economy principles by transforming wastewater from an environmental burden into a valuable resource [7].

Another important opportunity for resource recovery lies in the treatment and utilization of sludge generated during wastewater treatment processes. Sludge often contains significant amounts of organic matter that can be converted into energy through anaerobic digestion [18].

During this process, microorganisms break down organic compounds to produce biogas, which primarily consists of methane and carbon dioxide. The generated biogas can be used for electricity generation or heat production within the power plant, thereby contributing to energy efficiency and reducing reliance on external energy sources [19].

Furthermore, emerging technologies such as microbial fuel cells and thermochemical conversion processes offer promising pathways for converting wastewater-derived organic matter into energy. Although these technologies are still under development for large-scale industrial applications, they demonstrate the growing potential for integrating wastewater treatment with energy recovery systems.

Overall, adopting resource recovery strategies in biomass power plant wastewater management can significantly enhance environmental sustainability. By recovering water, nutrients, and energy from wastewater streams, power plants

can reduce waste generation, minimize environmental pollution, and improve resource efficiency.

#### IV. PROPOSED SUSTAINABLE WASTEWATER MANAGEMENT FRAMEWORK

Effective wastewater management in biomass power plants requires an integrated approach that combines conventional treatment technologies with advanced treatment and resource recovery processes. Traditional wastewater treatment systems are typically designed to meet discharge standards; however, they often fail to address the broader sustainability objectives associated with water reuse and resource recovery. To overcome these limitations, a sustainable wastewater management framework can be developed that incorporates circular resource utilization principles.

The proposed framework begins with the identification and segregation of different wastewater streams generated within the biomass power plant. Wastewater from boiler blowdown, cooling tower systems, ash handling units, and flue gas treatment systems may exhibit significantly different chemical and physical characteristics. Segregating these streams at the source allows for the implementation of targeted treatment processes, which can improve treatment efficiency and reduce operational costs. Following wastewater segregation, primary treatment processes such as screening, sedimentation, and equalization are applied to remove coarse particles and stabilize the wastewater flow. These processes are essential for protecting downstream treatment units and ensuring consistent treatment performance. After primary treatment, secondary treatment processes are employed to remove biodegradable organic pollutants. Biological treatment systems, including activated sludge processes or biofilm-based reactors, are commonly used for this purpose.

Once the majority of organic contaminants have been removed, advanced treatment technologies can be implemented to achieve higher levels of pollutant removal and enable water reuse.

Technologies such as membrane filtration, advanced oxidation processes, and electrochemical treatment systems can effectively remove dissolved contaminants, pathogens, and trace pollutants. The selection of appropriate treatment technologies depends on wastewater characteristics and intended reuse applications. A key feature of the proposed framework is the integration of resource recovery processes within the treatment system. Sludge generated during biological treatment can be directed to anaerobic digestion systems for biogas production. The resulting biogas can be utilized within the power plant to generate heat or electricity, thereby improving energy efficiency. Similarly, nutrient recovery processes can be incorporated to extract valuable compounds from wastewater streams.

The final stage of the framework involves the reuse of treated water within the biomass power plant. Recycled water can be utilized in cooling systems, ash handling operations, and other non-potable applications. By implementing such reuse strategies, the plant can significantly reduce its dependence on freshwater resources and minimize wastewater discharge. Overall, the proposed sustainable wastewater management framework promotes an integrated approach that combines wastewater treatment,

resource recovery, and water reuse. Such a system not only improves environmental performance but also contributes to the long-term sustainability of biomass power generation.

#### V. ENVIRONMENTAL AND ECONOMIC BENEFITS

The adoption of sustainable wastewater management strategies in biomass power plants offers significant environmental and economic advantages. By integrating wastewater treatment with resource recovery processes, power plants can reduce environmental pollution while simultaneously improving operational efficiency and resource utilization. From an environmental perspective, improved wastewater treatment systems reduce the discharge of pollutants into natural water bodies. Contaminants such as suspended solids, organic compounds, and dissolved salts can negatively impact aquatic ecosystems if released without proper treatment. Implementing advanced treatment technologies helps ensure that treated effluent meets environmental discharge standards, thereby protecting surrounding ecosystems and maintaining water quality.

Water reuse is another important environmental benefit associated with sustainable wastewater management. Biomass power plants typically require substantial quantities of water for cooling and other operational processes. By recycling treated wastewater within the plant, freshwater withdrawals from natural sources can be significantly reduced. This approach contributes to water conservation and helps mitigate the impacts of industrial water consumption on local water resources.

In addition to environmental benefits, sustainable wastewater management strategies can also provide considerable economic advantages. Water reuse reduces the cost associated with freshwater procurement and wastewater disposal.

For industries located in regions where water scarcity is a major concern, internal water recycling can provide substantial financial savings over the long term. Energy recovery from wastewater sludge further enhances the economic viability of integrated wastewater management systems. Biogas generated through anaerobic digestion can be used to supplement the energy requirements of wastewater treatment facilities or other plant operations. This reduces dependence on external energy sources and improves overall energy efficiency.

Moreover, recovering valuable resources such as nutrients or reusable water creates additional economic opportunities. The recovered materials may be reused internally or potentially marketed as by-products, depending on regulatory conditions and market demand. As environmental regulations become increasingly stringent, adopting sustainable wastewater management practices can also help industries avoid penalties associated with non-compliance. Overall, integrating wastewater treatment with resource recovery and water reuse strategies creates a more sustainable and economically viable approach to managing industrial wastewater. For biomass power plants, such practices support both environmental protection and efficient resource utilization, reinforcing the role of biomass energy in sustainable energy systems.

#### VI. CONCLUSION AND FUTURE SCOPE

Biomass power plants represent a promising renewable energy solution; however, their operations generate wastewater streams containing suspended solids, organic pollutants, dissolved salts, and trace metals. Effective wastewater management is therefore essential to ensure environmental protection and sustainable plant operation. This study reviewed the major sources and characteristics of wastewater generated in biomass power plants and evaluated various treatment technologies applicable to these effluents. Conventional treatment processes such as sedimentation and biological treatment remain important for removing suspended and biodegradable pollutants, while advanced technologies including membrane filtration, advanced oxidation processes, and electrochemical treatment offer improved removal efficiency and enable water reuse. The study also highlighted the potential of resource recovery from wastewater streams. Treated wastewater can be reused within plant operations, reducing freshwater consumption, while sludge generated during treatment can be utilized for energy recovery through processes such as anaerobic digestion. Integrating wastewater treatment with resource recovery strategies supports circular economy principles and enhances the overall sustainability of biomass energy systems.

Future research should focus on developing integrated and energy-efficient wastewater treatment systems that combine conventional and advanced technologies. The application of emerging tools such as real-time monitoring systems, artificial intelligence-based process control, and hybrid treatment technologies may further improve treatment efficiency and operational reliability.

Additionally, pilot-scale studies and techno-economic assessments are needed to evaluate the practical feasibility of implementing sustainable wastewater management frameworks in biomass power plants. Continued research in these areas will contribute to improving environmental performance and resource efficiency in renewable energy systems.

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