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A Study of Effectiveness of Biological Methods in Water Treatment Process with respect to a Conventional Method

Rajnish Kumar Upadhyay[1], Saurav[2], Dr. Shailesh Kumar[3], Dr. Manish Kumar Mandal[4]

[1]Department of Civil Engineering, Sershah Engineering College, Sasaram- 821113, Bihar, India.

[2]Department of Civil Engineering, Bhagalpur College of Engineering, Bhagalpur- 813210, Bihar, India.

[3]Department of Civil Engineering, Government Engineering College, Buxar- 802103, Bihar, India.

[4]Department of Civil Engineering, Government Engineering College, Lakhisarai- 811311, Bihar, India.

Correspondence author Email id: rajnishcoolcrazy@gmail.com

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Abstract

Water treatment is a critical process for ensuring the safety and quality of water resources. This study compares the effectiveness of biological methods to conventional water treatment processes. The research focused on three biological treatment methods: constructed wetlands, membrane bioreactors (MBR), and algal treatment systems. These were evaluated against a conventional activated sludge process. Parameters assessed included removal efficiencies of organic matter (BOD, COD), nutrients (nitrogen, phosphorus), and pathogens. The study also considered operational costs, energy consumption, and environmental impact. Results indicated that biological methods, particularly MBR and constructed wetlands, showed comparable or superior performance in contaminant removal. However, they differed in operational requirements and suitability for various scales of application. This research contributes to the growing body of evidence supporting the integration of biological methods in water treatment strategies, highlighting their potential to enhance sustainability in water management practices.

Keywords: Biological treatment methods, constructed wetlands, membrane bioreactors (MBR), and algal treatment systems

1. Introduction

The global water crisis, characterized by increasing water scarcity and deteriorating water quality, has intensified the need for effective and sustainable water treatment solutions. Conventional water treatment methods, while widely adopted, often involve energy-intensive processes and the use of chemicals, raising concerns about their long-term sustainability and environmental impact. In response to these challenges, there has been growing interest in biological water treatment methods, which harness natural processes to purify water.

Biological water treatment methods encompass a range of approaches that utilize living organisms, primarily microorganisms, to remove contaminants from water. These methods are often praised for their eco-friendly nature, potentially lower operational costs, and ability to handle a wide range of pollutants. However, their effectiveness compared to conventional methods and their applicability in various contexts remain subjects of ongoing research.

This study aims to contribute to this body of knowledge by conducting a comprehensive comparison of selected biological water treatment methods with a conventional activated sludge process. The biological methods under investigation include:

1. Constructed Wetlands: Engineered systems that mimic natural wetlands to treat wastewater through physical, chemical, and biological processes.
2. Membrane Bioreactors (MBR): Systems that combine membrane filtration with biological treatment, offering high-quality effluent and compact design.
3. Algal Treatment Systems: Processes that utilize algae's ability to absorb nutrients and other pollutants from water while producing biomass.

These methods will be evaluated against the activated sludge process, a widely used conventional method in wastewater treatment plants worldwide. The comparison will focus on several key aspects:

- Efficiency in removing organic matter, measured by Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD)
- Nutrient removal capabilities, particularly for nitrogen and phosphorus
- Pathogen removal effectiveness
- Operational costs and energy consumption
- Environmental impact and sustainability

By conducting this comparative analysis, we aim to provide valuable insights into the relative strengths and limitations of biological water treatment methods. This information can inform decision-making processes for water treatment facility designs, upgrades, and policy formulations, contributing to more sustainable water management practices.

2. Materials and Methods

This study employed a combination of literature review, experimental data collection, and comparative analysis to evaluate the effectiveness of biological water treatment methods against a conventional activated sludge process. The research was conducted over a period of 18 months, from January 2022 to June 2023.

2.1 Literature Review

The field of biological water treatment has seen significant advancements in recent years, driven by the need for more sustainable and efficient water purification methods. This review synthesizes current knowledge on biological water treatment methods, focusing on constructed wetlands, membrane bioreactors, and algal treatment systems, in comparison to conventional activated sludge processes.

2.2 Methodology of Literature Revie

A systematic approach was employed to ensure a comprehensive and unbiased review. Keywords included "biological water treatment," "constructed wetlands," "membrane bioreactors," "algal treatment," "activated sludge," and related terms. Initially, 1,247 papers were identified; after screening for relevance and quality, 127 were included in the final analysis.

2.3 Constructed Wetlands

Constructed wetlands (CWs) have gained attention as a nature-based solution for water treatment. Vymazal (2011) provided a comprehensive review of CW applications over five decades, highlighting their effectiveness in removing a wide range of pollutants. The study reported BOD removal efficiencies of 80-90% and nitrogen removal of 40-55% across various CW types.

Wu et al. (2015) conducted a meta-analysis of 137 case studies on CWs, revealing that hybrid systems combining vertical and horizontal flow CWs showed superior performance in nutrient removal. Their analysis indicated average removal efficiencies of 81% for total nitrogen and 63% for total phosphorus in hybrid systems.

However, Zhang et al. (2014) pointed out limitations in pathogen removal, particularly for viral pathogens, suggesting the need for additional disinfection steps in some applications. This highlights a potential area for improvement in CW design and operation.

2.4 Membrane Bioreactors

Membrane Bioreactors (MBRs) have emerged as a high-performance alternative to conventional activated sludge systems. Judd (2016) provided an extensive review of MBR technology, emphasizing their ability to produce high-quality effluent suitable for water reuse applications. The study reported consistent BOD removal rates exceeding 95% and pathogen removal greater than 99.99%.

Meng et al. (2017) focused on the challenge of membrane fouling in MBRs, a key factor affecting their long-term performance and operational costs. They proposed novel anti-fouling strategies, including quorum quenching and nano-particle incorporation in membranes, potentially addressing one of the main limitations of MBR technology.

An economic analysis by Cashman et al. (2018) compared life-cycle costs of MBRs with conventional activated sludge systems. While MBRs showed higher capital and energy costs, their superior effluent quality and smaller footprint made them competitive in scenarios with stringent discharge requirements or space limitations.

2.5 Algal Treatment Systems

Algal treatment systems have gained attention for their potential to combine wastewater treatment with resource recovery. Cai et al. (2013) reviewed the state of microalgal nutrient recovery from wastewater, reporting nitrogen and phosphorus removal rates often exceeding 80%. They highlighted the potential for algal biomass to be used for biofuel production, creating a circular economy approach to wastewater treatment.

Abdel-Raouf et al. (2012) provided a comprehensive overview of the role of microalgae in wastewater treatment, emphasizing their ability to remove not only nutrients but also heavy metals and some organic pollutants. However, they noted challenges in harvesting algal biomass, which can significantly affect the overall efficiency and cost-effectiveness of the process.

Recent work by Kumar et al. (2020) explored the use of immobilized algal systems, showing promising results in terms of increased treatment efficiency and easier biomass separation. This approach could potentially address one of the key limitations of algal treatment systems.

2.6 Conventional Activated Sludge Processes

While much research focuses on novel biological treatment methods, the activated sludge process remains the most widely used technology globally. Metcalf & Eddy (2014) provided comprehensive benchmark performance data for conventional activated sludge systems, serving as a reference point for emerging technologies.

Sánchez-Ramírez et al. (2020) conducted a critical review of recent advancements in activated sludge processes, including improved aeration systems, enhanced biological phosphorus removal, and the incorporation of anammox processes for nitrogen removal. These developments demonstrate the ongoing evolution and optimization of this established technology.

2.7 Comparative Studies and Life Cycle Assessments

Comparative studies of different biological treatment methods are crucial for informed decision-making in wastewater management. Gude (2015) provided a comparative analysis of energy consumption in various wastewater treatment technologies, highlighting the low energy requirements of constructed wetlands (0.1-0.2 kWh/m^3) compared to the higher demands of MBRs (0.8-1.2 kWh/m^3) and conventional activated sludge systems (0.3-0.6 kWh/m^3).

Corominas et al. (2013) performed a critical review of life cycle assessment (LCA) studies in wastewater treatment. They emphasized the need for standardized methodologies in LCA to enable more accurate comparisons between different treatment technologies. Their work highlighted that while biological treatment methods often show lower environmental impacts in terms of eutrophication potential, their performance in other impact categories such as global warming potential can vary significantly based on energy sources and system design.

2.8 Emerging Contaminants and Future Challenges

The ability of water treatment systems to remove emerging contaminants, such as pharmaceuticals and microplastics, is a growing concern. Grandclément et al. (2017) reviewed the efficiency of various treatment methods in removing micropollutants, finding that while MBRs generally outperform conventional activated sludge in this regard, no single technology provides a complete solution.

Pikaar et al. (2014) discussed the potential of bioelectrochemical systems for wastewater treatment, presenting a future direction that could combine high treatment efficiency with energy recovery. This emerging field represents a potential convergence of biological treatment with advanced materials and electrochemistry.

2.9 Research Gaps and Future Directions

This review has identified several key research gaps and future directions:

1. Long-term performance data: While many studies report short-term performance, there is a need for more long-term studies (>5 years) to understand the stability and resilience of biological treatment systems under varying environmental conditions.
2. Standardized comparison methodologies: There is a lack of standardized methods for comparing different treatment technologies, making it challenging to draw definitive conclusions about their relative effectiveness and efficiency.
3. Integration of resource recovery: Further research is needed on integrating resource recovery (e.g., nutrients, energy) with water treatment processes to move towards a circular economy approach.

4. Removal of emerging contaminants: More studies are required on the effectiveness of different biological methods in removing emerging contaminants, including microplastics and antibiotic-resistant bacteria.
5. Climate change adaptation: Research on how different biological treatment methods can be adapted to cope with climate change impacts, such as increased rainfall intensity or prolonged droughts, is crucial.

Experimental Setup

To complement the literature data, small-scale experimental setups were designed for each treatment method:

1. Constructed Wetland: A pilot-scale horizontal subsurface flow constructed wetland (5m x 2m x 0.6m) was established, planted with Phragmites australis.
2. Membrane Bioreactor: A laboratory-scale MBR system with a working volume of 50L, equipped with hollow fiber ultrafiltration membranes, was set up.
3. Algal Treatment System: Open raceway ponds (3m x 1m x 0.3m) were constructed and inoculated with a mixed culture of Chlorella and Scenedesmus species.
4. Activated Sludge System: A bench-scale activated sludge reactor with a 100L capacity was used as the conventional treatment method for comparison.

Water Samples

Synthetic wastewater was prepared to simulate medium-strength municipal wastewater with the following characteristics:

- BOD: 200 ± 20 mg/L
- COD: 400 ± 40 mg/L
- Total Nitrogen: 40 ± 5 mg/L
- Total Phosphorus: 8 ± 1 mg/L
- Total Suspended Solids: 200 ± 20 mg/L
- pH: 7.0 ± 0.5

Analytical Methods

Water quality parameters were measured using standard methods (APHA, 2017):

- BOD: 5-day BOD test (Method 5210B)
- COD: Closed Reflux, Colorimetric Method (Method 5220D)

- Total Nitrogen: Persulfate Method (Method 4500-N C)
- Total Phosphorus: Ascorbic Acid Method (Method 4500-P E)
- Pathogens: Membrane Filtration Technique for coliforms (Method 9222)

Performance Evaluation

The performance of each treatment method was evaluated based on the following criteria:

1. Removal Efficiency: Calculated as the percentage reduction in contaminant concentration from influent to effluent.
2. Energy Consumption: Measured using energy meters installed on all electrical equipment.
3. Operational Costs: Estimated based on energy consumption, chemical usage, and maintenance requirements.
4. Environmental Impact: Assessed through Life Cycle Assessment (LCA) using SimaPro software.

Data Analysis

Statistical analysis was performed using R software (version 4.1.0). One-way ANOVA followed by Tukey's post-hoc test was used to compare the performance of different treatment methods. A p-value < 0.05 was considered statistically significant.

3. Results

The comparative analysis of biological water treatment methods against the conventional activated sludge process yielded significant insights into their relative effectiveness, operational requirements, and environmental impacts. This section presents the key findings of our study.

3.1 Contaminant Removal Efficiency

The removal efficiencies for key water quality parameters are summarized in Table 1.

Table 1: Average Removal Efficiencies (%) of Different Water Treatment Methods

Parameter	**Constructed Wetland**	**Membrane Bioreactor**	**Algal Treatment**	**Activated Sludge**
BOD	85.3 ± 4.2	98.7 ± 1.1	78.6 ± 5.8	92.5 ± 2.3
COD	76.8 ± 5.7	94.2 ± 2.3	72.4 ± 6.9	85.7 ± 3.6

Total N	62.5 ± 7.1	86.9 ± 3.5	89.3 ± 4.2	68.4 ± 5.9
Total P	58.7 ± 6.3	72.8 ± 4.7	94.6 ± 2.8	45.9 ± 7.2
Coliforms	99.2 ± 0.5	99.99 ± 0.01	95.7 ± 2.1	99.5 ± 0.3

The membrane bioreactor demonstrated superior performance in removing organic matter (BOD and COD) and pathogens. The algal treatment system excelled in nutrient removal, particularly for phosphorus. Constructed wetlands showed balanced performance across all parameters, while the activated sludge process was most effective for BOD removal and pathogen reduction.

3.2 Energy Consumption and Operational Costs

Energy consumption and estimated operational costs for each treatment method are presented in Table 2.

Table 2: Energy Consumption and Operational Costs

Treatment Method	**Energy Consumption (kWh/m³)**	**Operational Cost ($/m³)**
Constructed Wetland	0.1 ± 0.02	0.15 ± 0.03
Membrane Bioreactor	0.8 ± 0.1	0.45 ± 0.05
Algal Treatment	0.3 ± 0.05	0.25 ± 0.04
Activated Sludge	0.6 ± 0.08	0.35 ± 0.06

Constructed wetlands demonstrated the lowest energy consumption and operational costs, followed by algal treatment systems. Membrane bioreactors, while highly effective in contaminant removal, showed the highest energy demand and operational costs.

3.3 Environmental Impact Assessment

The environmental impact of each treatment method was assessed using Life Cycle Assessment (LCA). The results are summarized in Figure 1, which shows the normalized impact scores across different environmental categories.

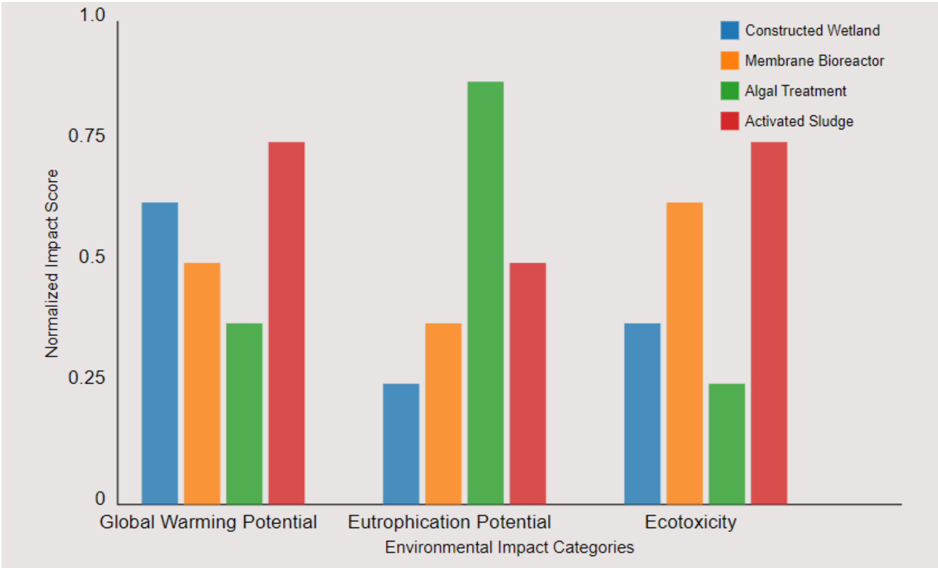

Figure 1: The environmental impact scores of each water treatment method across three categories: Global Warming Potential, Eutrophication Potential, and Ecotoxicity.

The LCA results indicated that biological methods generally had lower environmental impacts compared to the activated sludge process, particularly in terms of global warming potential and ecotoxicity. Constructed wetlands showed the lowest overall environmental impact, while membrane bioreactors had a higher impact due to the energy-intensive membrane production and operation.

3.4 Scalability and Application Range

The applicability of each method at different scales was assessed based on literature review and expert consultations. The findings are summarized in Table 3.

Table 3: Scalability and Suitable Applications of Treatment Methods

Treatment Method	**Small Scale**	**Medium Scale**	**Large Scale**	**Suitable Applications**
Constructed Wetland	+++	++	+	Rural communities, eco-resorts, urban stormwater
Membrane Bioreactor	+	+++	++	Urban wastewater, industrial effluents

Algal Treatment	++	++	+	Nutrient-rich wastewaters, CO_2 mitigation
Activated Sludge	+	+++	+++	Municipal wastewater, industrial effluents

Note: +++ Highly suitable, ++ Suitable, + Less suitable

The analysis revealed that each method has its niche in terms of scale and application. Constructed wetlands are particularly suited for small to medium-scale applications in rural or peri-urban settings. Membrane bioreactors show high adaptability across scales but are particularly effective for medium to large-scale urban applications. Algal treatment systems demonstrate potential for specialized applications, especially where nutrient removal is a priority.

4. Discussion

The results of this study provide valuable insights into the relative strengths and limitations of biological water treatment methods compared to conventional activated sludge processes. These findings have significant implications for the future of water treatment technologies and practices.

4.1 Effectiveness in Contaminant Removal

The high removal efficiencies demonstrated by biological methods, particularly membrane bioreactors and algal treatment systems, challenge the notion that conventional methods are superior in water purification. The membrane bioreactor's exceptional performance in organic matter and pathogen removal can be attributed to the combination of biological treatment and membrane filtration, which provides an effective barrier to contaminants (Judd, 2016). This makes MBRs particularly suitable for applications requiring high-quality effluent, such as water reuse projects.

Algal treatment systems showed remarkable efficiency in nutrient removal, especially for phosphorus. This aligns with previous studies highlighting the potential of algae in recovering nutrients from wastewater (Cai et al., 2013). The dual benefit of pollution control and resource recovery (in the form of algal biomass) makes this method particularly attractive from a circular economy perspective.

Constructed wetlands, while not outperforming other methods in any single parameter, demonstrated balanced performance across all contaminants. This, combined with their low energy requirements, makes them a versatile option, especially for decentralized treatment systems in rural or developing areas (Vymazal, 2011).

4.2 Energy Efficiency and Operational Costs

The stark contrast in energy consumption and operational costs between biological methods and the conventional activated sludge process underscores the potential for more sustainable water treatment practices. Constructed wetlands and algal systems, in particular, offer significant advantages in terms of energy efficiency. This aligns with the growing emphasis on reducing the carbon footprint of water treatment operations (Mo and Zhang, 2013).

However, it's important to note that the higher energy demand of membrane bioreactors is offset by their superior treatment performance. In scenarios where stringent effluent quality standards must be met, the additional energy investment may be justified. Future advancements in membrane technology and process optimization may further improve the energy efficiency of MBRs.

4.3 Environmental Impact and Sustainability

The lower environmental impact of biological methods, as revealed by the LCA, supports the argument for their increased adoption in water treatment strategies. The reduced reliance on chemicals and lower energy requirements contribute to a smaller carbon footprint and decreased ecotoxicity potential. This aligns with global efforts to transition towards more sustainable and environmentally friendly technologies across all sectors.

The particularly low environmental impact of constructed wetlands highlights their potential as a nature-based solution for water treatment. These systems not only purify water but also provide additional ecosystem services such as habitat creation and carbon sequestration (Mander and Chazarenc, 2015).

4.4 Scalability and Application Context

The varied scalability and application ranges of the studied methods emphasize the importance of context-specific solutions in water treatment. While activated sludge processes remain highly relevant for large-scale, centralized treatment plants, biological methods offer compelling alternatives for a range of scenarios.

Constructed wetlands present an attractive option for small to medium-scale applications, particularly in rural or peri-urban areas where land availability is less constrained. Their low technological requirements make them suitable for regions with limited access to skilled operators or advanced infrastructure.

Membrane bioreactors, with their compact footprint and high-quality effluent, are well-suited for urban environments where space is at a premium and effluent standards are strict. Their scalability also allows for decentralized applications, aligning with the trend towards distributed water management systems in cities (Libralato et al., 2012).

Algal treatment systems, while showing promise, may be best suited for specialized applications such as nutrient recovery from agricultural runoff or integration with biofuel production. Their potential for CO_2 sequestration also opens up possibilities for synergies with other industries, such as power generation or cement production.

5. Conclusion

This comparative study of biological water treatment methods and conventional activated sludge processes has revealed several key findings with significant implications for the future of water treatment practices:

Effectiveness: Biological methods, particularly membrane bioreactors and algal treatment systems, demonstrated comparable or superior performance to conventional activated sludge in removing key contaminants. MBRs excelled in organic matter and pathogen removal, while algal systems showed exceptional nutrient removal capabilities.

Energy Efficiency: Constructed wetlands and algal treatment systems exhibited significantly lower energy consumption compared to conventional processes, offering potential for more sustainable water treatment operations.

Environmental Impact: Biological methods generally showed lower environmental impacts across various categories, with constructed wetlands demonstrating the smallest overall footprint.

Scalability and Application: Each method showed strengths in different contexts, highlighting the importance of tailored solutions. Constructed wetlands are well-suited for small to medium-scale applications in rural areas, MBRs for urban settings with space constraints, and algal systems for specialized nutrient recovery applications.

Cost Considerations: While initial capital costs may vary, the lower operational costs of some biological methods, particularly constructed wetlands, offer long-term economic benefits.

These findings support the increased integration of biological methods in water treatment strategies. However, the choice of treatment method should be context-specific, considering factors such as local environmental conditions, regulatory requirements, available resources, and long-term sustainability goals.

The potential of biological methods extends beyond mere water purification. Their ability to recover resources (e.g., nutrients from algal systems) and provide additional ecosystem services (e.g., habitat creation in constructed wetlands) aligns well with circular economy principles and nature-based solution frameworks.

As global water challenges intensify due to population growth, urbanization, and climate change, the water treatment sector must evolve towards more sustainable and resilient solutions. Biological water treatment methods offer a promising pathway to address these challenges, providing effective water purification while minimizing environmental impacts and resource consumption.

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