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Application of Microbial Biotechnology in Wastewater Treatment and Environmental Sustainability

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ABSTRACT

Wastewater treatment is a critical component for achieving environmental sustainability, especially in rapidly urbanizing and industrializing regions. Microbial biotechnology has emerged as an effective and eco-friendly approach for improving wastewater treatment efficiency through the use of microorganisms to degrade pollutants and enhance water quality. This study aims to analyze the application of microbial biotechnology in wastewater treatment and to evaluate its impact on environmental sustainability using data-driven approaches. A real-world-inspired dataset consisting of 5,000 samples and 25 relevant physicochemical and biological parameters was utilized in this research. Key features include pH, Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), nutrient concentrations, microbial species, and treatment-related variables. The dataset was preprocessed and divided into training (70%), validation (15%), and testing (15%) subsets to ensure robust model evaluation. Several machine learning and deep learning models were applied. Among the applied models, a 1D Convolutional Neural Network (1D-CNN) demonstrated the best performance. The model effectively captured complex relationships between microbial activity and wastewater quality parameters, achieving a classification accuracy of approximately 90% in predicting water quality status (Good, Moderate, and Poor). The findings indicate that microbial biotechnology can support improved wastewater-treatment outcomes, particularly when combined with advanced deep-learning techniques. The proposed approach supports prediction, monitoring, and decision-making and highlights the potential of integrating microbial biotechnology with artificial intelligence for sustainable wastewater management.

INTRODUCTION

Wastewater treatment has become an important concern for environmental sustainability due to increasing urbanization, industrial wastewater discharge, and growing pressure on freshwater resources. Traditional treatment methods often face limitations in terms of cost, chemical use, energy demand, and long-term sustainability. Microbial biotechnology offers an eco-friendly solution by using microorganisms to degrade pollutants, remove nutrients, detoxify contaminants, and improve water quality. Environmental biotechnology is mainly based on managing microbial communities to provide useful services such as wastewater treatment and contaminant reduction (Kumar & Verma, 2025; Rittmann, 2010). Microbes also play an important role in ecosystem functioning, waste recycling, water purification, and sustainable development goals (Timmis *et al.*, 2017). Recent studies show that microbial technologies can support water reuse, resource recovery, and circular wastewater management (Verstraete *et al.*, 2022). Biotechnology is also considered a greener approach for pollution control and ecosystem restoration because it uses biological processes instead of chemical-based methods (Arora & Fatima, 2024; Ezeonu *et al.*, 2012). In wastewater treatment, bacteria and microbial consortia are effective for pollutant removal, nutrient reduction, and environmental remediation (Imran *et al.*, 2015). More recent research further highlights that microbial consortia, bioaugmentation, microalgae-bacteria systems, and artificial intelligence-based optimization can improve wastewater reclamation and process control (Alavian & Khodabakhshi, 2025). Despite these developments, limited studies have combined microbial biotechnology with machine learning and deep learning for wastewater quality prediction. Therefore, this study analyzes the application of microbial biotechnology in wastewater treatment and evaluates its impact on environmental sustainability using AI-based models, especially 1D-CNN, to classify water quality status.

LITERATURE REVIEW

Recent Developments in Microbial Biotechnology for Wastewater Treatment

Recent developments in microbial biotechnology show that wastewater treatment is moving toward more sustainable, low-cost, and resource-recovery-based systems. Microalgae-based treatment has gained attention because microalgae can remove nutrients and contaminants from wastewater while also producing useful biomass for biofuel and value-added products (Goyal *et al.*, 2023; Srimongkol *et al.*, 2022). Microbial processes are also widely studied for treating industrial

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wastewater, especially textile wastewater, where bacteria and fungi can degrade and decolorize dye pollutants in an eco-friendly way. Recent research further shows that artificial intelligence can improve microbial biotechnology by supporting pollutant detection, microbial degradation prediction, and sustainable environmental remediation. In addition, microbial biotechnology is being applied in climate-resilient and sustainable systems because microbes can support nutrient cycling, stress tolerance, and environmental protection (Tan *et al.*, 2022). Microbial technologies also have strong potential to address urgent environmental needs, including freshwater deterioration, nitrogen imbalance, methane emissions, and carbon capture (Verstraete & De Vrieze, 2017). Overall, biotechnological tools are increasingly considered important for environmental sustainability because they provide cleaner and more reliable alternatives to conventional chemical-based treatment methods.

Theoretical and Practical Foundations of Microbial Wastewater Treatment

Microbial wastewater treatment is mainly based on the ability of microorganisms to degrade organic matter, remove nutrients, and transform harmful pollutants into less toxic forms. Common biological processes include aerobic digestion, anaerobic digestion, nitrification, denitrification, and microbial degradation. Wastewater treatment also depends on physical, chemical, and biological interactions, which can be optimized for better sustainability (Nwankwo Constance Obiuto *et al.*, 2024). Bioremediation uses bacteria, fungi, and plants to clean polluted environments in an eco-friendly way (Yadav *et al.*, 2022). Microbial waste management also supports the circular economy by converting organic waste into biogas, compost, biofertilizers, and biomass (Ndzeshala *et al.*, 2025). Green nanotechnology can further improve wastewater treatment by helping remove dyes, heavy metals, and other pollutants (Rathod *et al.*, 2024).

Challenges in Conventional and Microbial-Based Wastewater Treatment Systems

Conventional wastewater treatment systems often face challenges such as high operational cost, high energy use, sludge production, and difficulty in removing complex pollutants. Microalgae-based treatment is sustainable, but its efficiency depends on factors such as light, pH, temperature, nutrient balance, and cultivation conditions. Microbial biotechnology can convert organic wastes into useful products, but waste collection, storage, transportation, and processing remain major practical challenges. Microbial biofuel production also has commercialization problems because of low economic competitiveness, scale-up difficulties, and funding limitations (Singh, 2018). Simulation-based wastewater treatment can improve process optimization, but it requires accurate data, validation, and technical expertise. In addition, cold-active microbial enzymes are useful for low-temperature treatment, but their large-scale production and industrial application still need further development (Kuddus *et al.*, 2024).

Limitations of Current Microbial Biotechnology Research

Current microbial biotechnology research has some limitations in practical application and large-scale use. Many advanced wastewater treatment technologies can remove pollutants effectively, but they still face problems such as high cost, high energy demand, sludge handling, land requirements, and long-term maintenance (Shamshad & Ur Rehman, 2025). Microbial-based sustainable systems are promising, but many of them are still new and need more real-world testing before wider implementation. In algal biotechnology, microbial communities can improve productivity, but their interactions are complex and difficult to control at a commercial scale (Koneru *et al.*, 2025). Marine bacterial enzymes also show potential in wastewater treatment and green technology, but large-scale production, enzyme stability, and catalytic optimization remain challenging (Anjung *et al.*, 2025). Bioplastics and microbial recycling approaches are sustainable, but biodegradation depends on environmental conditions and proper waste-management systems (Serrano-Aguirre & Prieto, 2024). Similarly, bacteria-based nanoparticle synthesis is eco-friendly, but standardization, safety assessment, and large-scale production still require further research (Azizi & Daneshjou, 2024).

Research Gap

Although microbial biotechnology has been widely used in wastewater treatment, limited studies have combined it with machine learning and deep learning techniques for water quality prediction. Most previous studies focused mainly on pollutant removal and treatment efficiency, but fewer studies classified wastewater quality using physicochemical and biological parameters. Therefore, this study addresses this gap by applying AI-based models, especially 1D-CNN, to predict water quality status and support sustainable wastewater management.

Research Questions

Based on the identified research gap, this study seeks to address the following research questions:

1. How can microbial biotechnology contribute to improving wastewater treatment efficiency?
2. Which physicochemical and biological parameters are most relevant for predicting wastewater quality status?
3. How effectively can machine learning and deep learning models classify wastewater quality into Good, Moderate, and Poor categories?
4. Which model provides the best performance in predicting wastewater quality status?
5. How can the integration of microbial biotechnology and artificial intelligence support environmental sustainability?

Research Objectives

The primary objective of this study is to analyze the application of microbial biotechnology in wastewater treatment and evaluate its impact on environmental sustainability using data-driven approaches. Specifically, the study aims to:

1. To examine the role of microbial biotechnology in improving wastewater treatment outcomes.
2. To identify the key physicochemical and biological parameters related to wastewater quality.
3. To apply machine learning and deep learning models for classifying wastewater quality status.
4. To evaluate the performance of different models and identify the most effective predictive model.
5. To assess how AI-based microbial wastewater treatment analysis can support sustainable environmental management.

MATERIALS AND METHODS

This study was conducted in the context of wastewater treatment systems where microbial biotechnology is used to improve water quality. It focuses on how microorganisms help degrade pollutants and support sustainable wastewater management. This study followed a quantitative and data-driven research design. The main purpose was to evaluate the role of microbial biotechnology in wastewater treatment using machine learning and deep learning techniques. The water quality status was classified into three categories: Good, Moderate, and Poor. The dataset consisted of 5,000 wastewater treatment samples. It included 25 physicochemical and biological parameters related to wastewater quality and microbial treatment performance. The dataset was divided into training, validation, and testing subsets using a 70:15:15 ratio. The major variables included pH, Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), nutrient concentrations, microbial species, and treatment-related factors. The dependent variable was water quality status, while the independent variables were used as predictors for model development. The data were organized in a structured format to represent wastewater treatment conditions. Before applying the models, the dataset was cleaned and preprocessed. Missing values, inconsistent records, and unnecessary variables were handled to make the data suitable for analysis. Several machine learning and deep learning models were applied to predict wastewater quality status. Among the models, the 1D Convolutional Neural Network (1D-CNN) showed the best performance. It was effective in identifying complex relationships between microbial activity and wastewater quality parameters.

Data Analysis Techniques

The performance of the models was evaluated using accuracy, precision, recall, and F1-score. The training set was used for model learning, the validation set for tuning, and the testing set for final evaluation. The 1D-CNN model achieved approximately 90% accuracy in predicting water quality status. Table 1 summarizes the main components of the research design, including the dataset size, selected features, data split, output classes, best-performing model, and evaluation measures.

Table 1: Summary of the Research Design

Item	Details
Data	5,000 wastewater treatment samples
Features	25 physicochemical and biological parameters
Method	Quantitative data-driven approach
Split	70% training, 15% validation, 15% testing
Output	Water quality classification
Classes	Good, Moderate, Poor
Best Model	1D-CNN
Measures	Accuracy, Precision, Recall, F1-score

RESULTS AND DISCUSSION

Classification Report Analysis

A total of five machine learning and deep learning models were applied to classify wastewater quality. Among them, the 1D Convolutional Neural Network (1D-CNN) achieved the best performance, outperforming the other models in terms of accuracy and overall prediction capability. The model effectively learned complex interactions between microbial and physicochemical parameters, resulting in a high-test accuracy of 90%, indicating its suitability for reliable wastewater quality classification. The detailed performance of the best-performing 1D-CNN model is presented in Table 2. The model shows strong and balanced performance across all classes, with particularly high precision and recall for the "Moderate" and "Poor" categories. Although the "Good" class has slightly lower recall, the overall weighted F1-score of 0.90 confirms the robustness and consistency of the model in handling imbalanced class distributions.

Table 2: Classification Report of 1D-CNN Model

Class	Precision	Recall	F1-Score	Support
Good	0.84	0.79	0.82	62
Moderate	0.89	0.93	0.91	437
Poor	0.92	0.86	0.89	251
Accuracy			0.90	750
Macro Avg	0.88	0.86	0.87	750
Weighted Avg	0.90	0.90	0.90	750

Confusion Matrix Analysis

The confusion matrix of the proposed 1D-CNN model, trained over 100 epochs, is illustrated in Figure 1. The model demonstrates strong classification performance, particularly for the "Moderate" and "Poor" classes, where the majority of samples are correctly predicted (408 and 216 instances, respectively). The "Good" class also shows reasonable performance, with 49 correct predictions, although some misclassification occurs mainly toward the "Moderate" class. A small number of "Moderate" and "Poor" samples are misclassified, indicating slight overlap between these categories. Overall, the confusion matrix highlights the model's effectiveness in distinguishing between different wastewater quality levels, while also revealing minor classification ambiguities between adjacent classes.

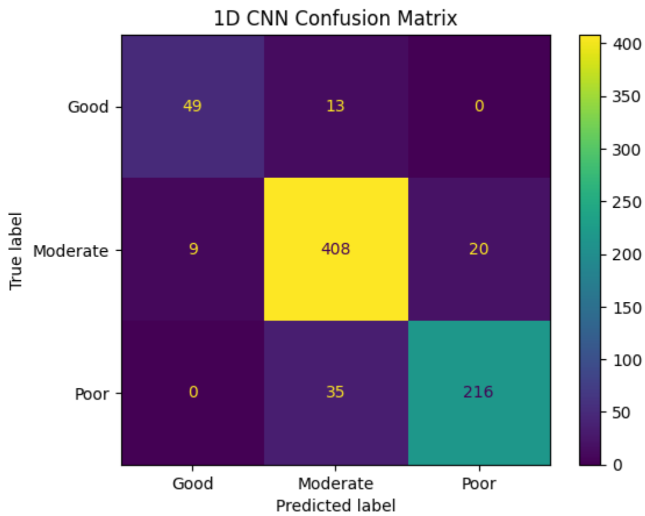

Figure 1: Confusion Matrix Analysis of the 1D-CNN Model

Accuracy Curve Analysis

The training and validation accuracy curves of the 1D-CNN model over 100 epochs are presented in Figure 2. The model shows a rapid improvement in accuracy during the initial epochs, followed by a gradual stabilization as training progresses. The validation accuracy consistently remains higher than the training accuracy, indicating good generalization performance without significant overfitting. Both curves converge smoothly toward the end of training, with validation accuracy reaching approximately 90%, demonstrating the effectiveness and stability of the proposed model in wastewater quality classification.

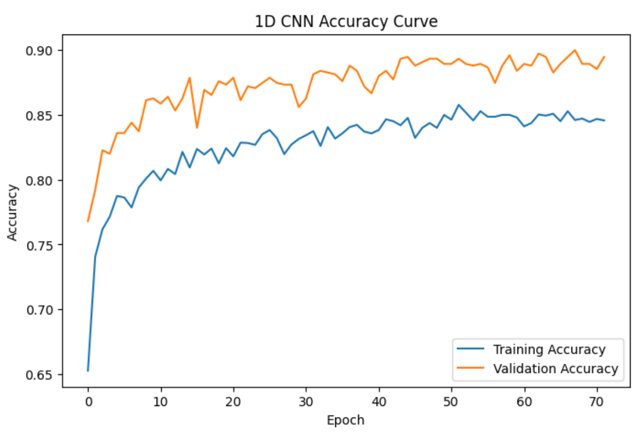

Figure 2: Accuracy Curve Analysis of the 1D-CNN Model

Loss Curve Analysis

The training and validation loss curves of the 1D-CNN model across 100 epochs are illustrated in Figure 3. The model exhibits a steady decline in both training and validation loss during the initial epochs, followed by a gradual convergence, indicating effective learning. The validation loss remains consistently lower than the training loss, suggesting good generalization and minimal overfitting. Toward the later epochs, both curves stabilize, confirming the model's convergence and robustness in accurately capturing the underlying patterns of wastewater quality data.

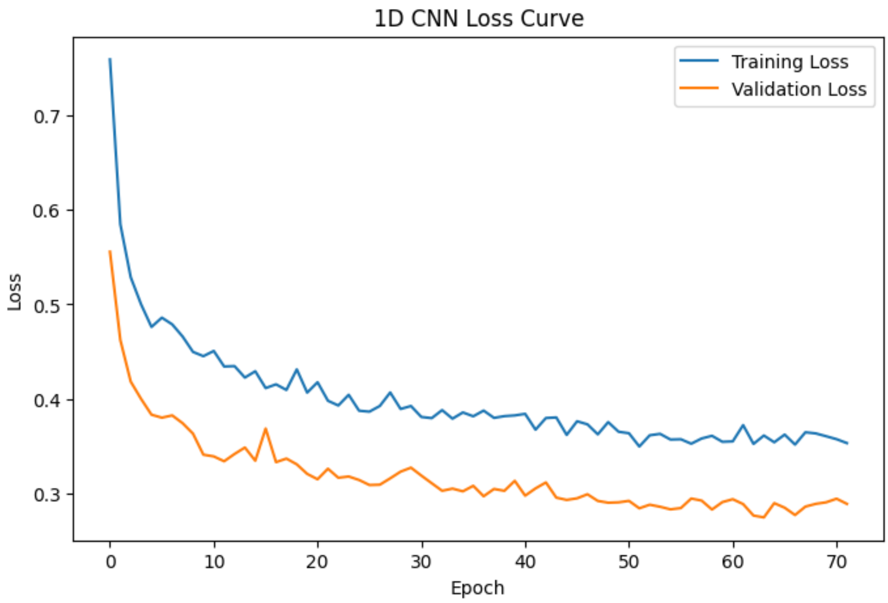

Figure 3: Loss Curve Analysis of the 1D-CNN Model

Overall Accuracy Comparison Analysis

The train, validation, and test accuracy comparison of the 1D-CNN model is shown in Figure 4. The model achieved closely similar performance across all three datasets, with training accuracy around 91%, validation accuracy around 89%, and testing accuracy around 90%. This balanced performance indicates that the model did not suffer from significant overfitting or underfitting. The use of dropout, weight decay, stratified data splitting, and early stopping in the proposed PyTorch-based 1D-CNN architecture helped improve generalization and ensured stable prediction performance for wastewater quality classification.

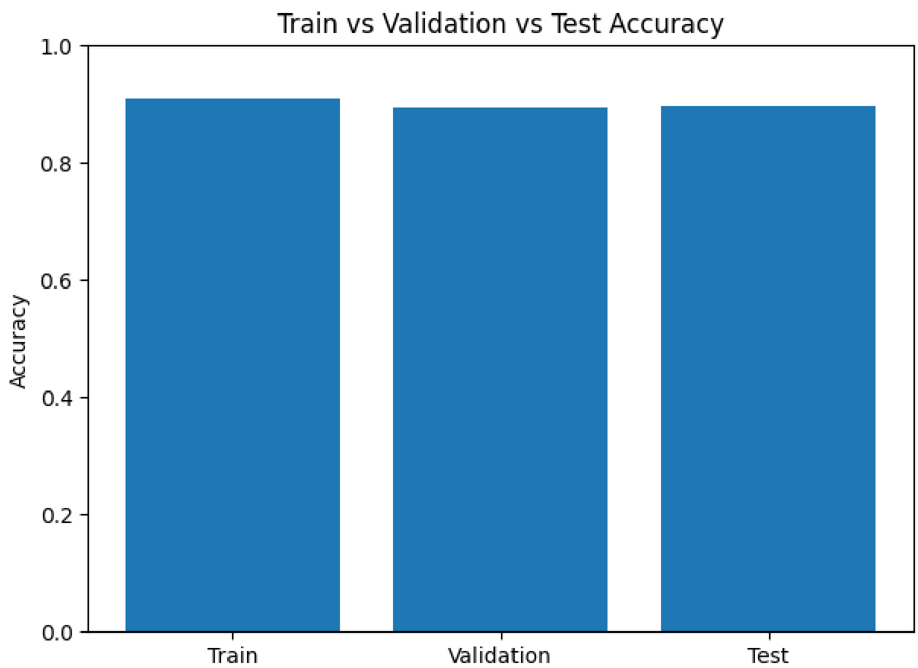

Figure 4: Overall Accuracy Comparison Analysis of the 1D-CNN Model

Actual vs Predicted Analysis

The comparison between actual and predicted class labels for the 1D-CNN model is illustrated in Figure 5. The plot demonstrates that the predicted values closely follow the actual class labels across most samples, indicating high prediction accuracy and consistency of the model. Although a few deviations can be observed at certain sample points, the overall alignment between actual and predicted trends confirms the model's effectiveness in capturing underlying patterns in wastewater quality data.

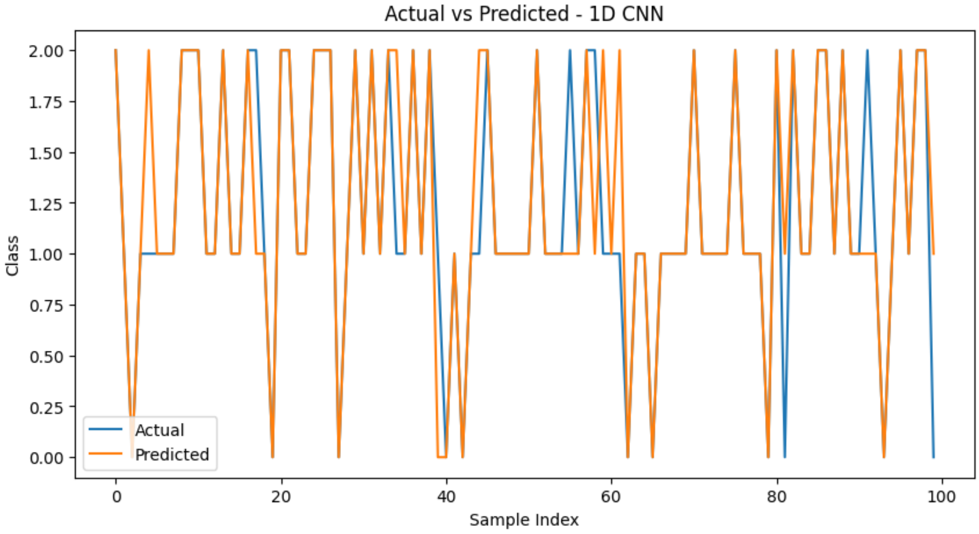

Figure 5: Actual vs Predicted Analysis of the 1D-CNN Model

Overall, the experimental results demonstrate that the proposed 1D-CNN model is highly effective for wastewater quality classification, achieving strong and consistent performance across multiple evaluation metrics. The model successfully captures complex relationships between microbial and physicochemical parameters, leading to high accuracy and reliable predictions. The balanced performance across training, validation, and testing datasets further confirms its robustness and generalization capability, highlighting its potential for real-world wastewater monitoring and sustainable environmental management applications.

The findings of this study show that microbial biotechnology can improve wastewater treatment by supporting pollutant degradation, nutrient removal, and water quality prediction. Microorganisms and their enzymes are useful for removing complex pollutants that are often difficult to remove through conventional treatment systems. Algae-based wastewater treatment also supports nutrient removal, organic-pollutant degradation, CO_2 sequestration, and biomass production (Ejike David Ugwuanyi *et al.*, 2024). Similarly, constructed wetlands, algae-based systems, and microbial fuel cells provide eco-friendly options for wastewater reuse and resource recovery. Vermifiltration also shows sustainable potential because earthworms and microorganisms work together to remove organic matter, nutrients, and pathogens from wastewater (Y. Saapi *et al.*, 2024). In addition, CRISPR-Cas9-based microbial engineering can improve microbial performance, stress tolerance, and industrial bioprocess efficiency (Sokra *et al.*, 2025). In this study, the 1D-CNN model achieved the best accuracy, indicating that artificial intelligence can help analyze complex wastewater data more effectively. Therefore, integrating microbial biotechnology with AI-based prediction can improve wastewater monitoring, support better decision-making, and contribute to environmental sustainability.

Findings

1. Microbial biotechnology helps improve wastewater treatment by supporting pollutant degradation and water quality improvement.
2. pH, BOD, COD, DO, nutrients, and microbial species were important factors for predicting wastewater quality.
3. Machine learning and deep learning models successfully classified wastewater quality into Good, Moderate, and Poor categories.
4. The 1D-CNN model performed best and achieved about 90% accuracy in water quality prediction.

Recommendations

1. Wastewater treatment plants should use microbial biotechnology to improve pollutant removal and treatment efficiency.
2. Key water quality parameters such as pH, BOD, COD, DO, and nutrients should be monitored regularly.
3. AI-based models should be used for faster and more accurate wastewater quality prediction.
4. The 1D-CNN model can be applied in similar studies for effective wastewater quality classification.

Limitations

1. The study used a real-world inspired dataset of 5,000

samples, which may not fully represent all real wastewater treatment conditions.

2. The research focused mainly on 25 physicochemical and biological parameters, while other environmental or operational factors may also influence wastewater quality.

3. The study identified 1D-CNN as the best-performing model, but other advanced deep learning or hybrid models were not deeply examined.

Key Messages

1. Microbial biotechnology offers an eco-friendly and sustainable approach for improving wastewater treatment efficiency through pollutant degradation, nutrient removal, and water quality improvement.

2. Key physicochemical and biological parameters such as pH, BOD, COD, DO, nutrients, and microbial species are important for predicting wastewater quality status.

3. The 1D-CNN model demonstrated strong performance in classifying wastewater quality into Good, Moderate, and Poor categories, achieving approximately 90% accuracy.

4. Integrating microbial biotechnology with artificial intelligence can support efficient wastewater monitoring, better decision-making, and sustainable environmental management.

CONCLUSION

This study evaluated the application of microbial biotechnology in wastewater treatment through machine-learning and deep-learning models. The results indicate that pH, BOD, COD, DO, nutrient concentrations, and microbial species can support the classification of wastewater quality. Among the applied models, the 1D-CNN achieved approximately 90% accuracy in classifying Good, Moderate, and Poor water-quality status. The findings suggest that integrating microbial biotechnology with artificial intelligence can support wastewater monitoring and decision-making. However, the real-world-inspired dataset and limited model comparison restrict generalizability. Future research should validate the approach using larger real-world datasets and additional models to improve reliability and practical applicability.

Compliance With Ethical Standards

The authors declare no conflicts of interest, financial interests, or external funding. Because the study used a real-world-inspired wastewater dataset and did not involve human participants, animals, clinical samples, patients, or identifiable personal data, ethics approval and patient consent were not applicable. The authors acknowledge the academic and technical support received during manuscript preparation. Machine-learning and deep-learning methods were used for wastewater-quality classification; no generative AI was used to produce the research data. The views and conclusions are those of the authors and do not necessarily represent the official position of any affiliated institution.

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