Engineering a Sustainable Future: The Convergence of AI, Environmental, Chemical, Wastewater, and Mechanical Innovations

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Abstract
Sustainable wastewater management requires integrated environmental, chemical, mechanical, and data-driven assessment, particularly in urban-industrial river systems such as Kanpur along the Ganga. This study evaluated river-water quality and wastewater treatment performance by linking conventional pollution indicators with AI-oriented sustainability interpretation. Recent CPCB/UPPCB-based datasets and STP/CETP monitoring values were examined for Ganga monitoring points at Bithoor, Ranighat, and Jajmau Bridge, and for 130 MLD STP Jajmau, 42 MLD STP Sajari, and 36 MLD CETP Jajmau. The selected parameters included pH, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, and total suspended solids. Descriptive statistics, comparative assessment, and correlation-based interpretation were applied to identify pollution patterns and treatment-performance differences. River-water results showed slightly alkaline pH across monitoring locations, while BOD increased toward Jajmau Bridge, indicating higher organic pollution pressure. Treatment-unit comparison showed that municipal STPs had lower pollution loads than the CETP. The 36 MLD CETP Jajmau recorded the highest BOD, COD, and TSS values, indicating critical treatment stress and suspended-solid removal limitations. Higher BOD was associated with reduced dissolved oxygen. The findings highlight the need for stronger effluent control, mechanical optimization, chemical monitoring, and AI-enabled anomaly detection to support real-time decision-making, compliance assessment, and Ganga River protection.

Keywords: Wastewater treatment; Artificial intelligence; Ganga River; STP/CETP performance; Sustainable engineering

1. Introduction

The importance of wastewater management has grown in the recent times, due to the interdependency of urban development, industrial discharge, river pollution, chemical pollution and resource scarcity. Wastewater is no longer considered only a form of environmental pollution but also a source of resource recovery. The recent findings related to food processing wastewaters indicate the need to develop wastewater treatment methods that would focus not only on treating the wastewater but also on its resource recovery and reducing emissions so as not to exceed the planet's sustainability threshold (Durkin et al., 2024). Additionally, the innovations associated with biorenewable resource waste systems show that it is possible to integrate wastewater within broader sustainable processes (Guo et al., 2023).

The Ganga River is among the most vital river systems in India, but it suffers from considerable pollution due to domestic wastewater, industrial effluents, ritual practices, and urban run-off. It should be noted that Kanpur city of the state of Uttar Pradesh holds particular importance in being an urban-industrial complex located on the banks of the Ganga River and associated with tannery-related water waste and sewage. In such a scenario, the necessity of having treatment facilities, like sewage treatment plant and common effluent treatment plant, becomes all the more crucial to reduce pollutants before their release into the river.

The chemical aspect of wastewater treatment becomes especially significant considering the differences between pollutants regarding their biodegradability, oxidation/reduction potential, toxicity, and longevity. COD and BOD are commonly used to denote the amount of chemicals/organic contaminants present, whereas pH shows the stability of these contaminants chemically. Moreover, TSS is an indicator of the quantity of suspended substances in the water potentially affecting sedimentation. Studies concerning the development of the process of wastewater treatment have revealed that

the effectiveness of the procedure is determined by various parameters including the nature of pollutants, their biological breakdown, system design, and control (Kacaribu et al., 2025). In addition, microbial fuel cell technology and other similar technologies indicate the possibility of harnessing the potential of wastewater as a source of energy (Dwivedi et al., 2022).
The relevance of artificial intelligence and data-driven techniques in this case is growing due to the fact that wastewater treatment plants produce data that could be used for forecasting and optimizing. In water-related processes, the application of modern monitoring and control strategies has shown positive results in improving efficiency and reliability (Abioye et al., 2020). The use of fuzzy inference and emissions analysis has also been recommended in the sustainable design of chemical processes, suggesting that computing technologies might help with decision-making in the environmental context (Guzman-Urbina et al., 2022). Microalgae-based biorefinery and phycoremediation might be expected in the future wastewater systems through AI.
Operational and mechanical improvements are equally important because of the significance of pumps, aeration processes, hydraulic loading, settling tanks, sludge treatment, and control of the system itself in wastewater treatment. According to research conducted regarding the dynamic performance and the control of the system, it is important to pay attention to control engineering because it ensures efficient performance of infrastructure (Hashmi et al., 2023). On an urban level, the use of technology and management of resources is considered one of the ways of increasing the sustainability of cities (Hui et al., 2023).
While much has been achieved, there still is a lack of work that links modern data on Kanpur's wastewater and River Ganga with environmental, chemical, mechanical, and artificial intelligence-based considerations in terms of sustainability. As such, the main goal of this paper is to assess wastewater treatment processes and water pollution levels in River Ganga in Kanpur using up-to-date data by CPCB and UPPCB, as well as STPs and CETPs. In this regard, the study will focus on pH, BOD, COD, TSS, and DO measurements.

2. Literature review

The process of wastewater treatment can be said to form a key component of sustainable engineering since it plays a role in facilitating the reduction of pollution, improvement in effluent quality, recycling of water, and resource efficiency. In the current trends in sustainability science, wastewater is now being viewed not as waste but as a resource that can be recovered. The importance of resource recovery and emissions reduction in food processing wastewater is highlighted by Durkin et al. (2024), while the importance of biorenewable resource waste systems and modeling in sustainable processes is highlighted by Guo et al. (2023). In the field of sustainability, other research has demonstrated potential for enhancing environmental management and resilience through the application of smart technologies and reuse systems (Hui et al., 2023; Rowan, 2023).
Environmental and chemical indicators are crucial in the evaluation of the efficiency of wastewater treatment processes. Some of the parameters that can be quantified and which show the levels of pollution, process stability, and quality of effluents are COD, BOD, pH, suspended solids, sedimentation, conductivity and influent flow. The COD indicator is especially important as it determines the chemical strength of wastewater pollution and its ability to decrease oxidizable pollutants. BOD levels indicate the presence of biodegradable organic contaminants in wastewater, while suspended solids and sedimentation indicate solids' removal and behavior. Although Sharma et al. (2022) alludes to advanced materials used for environmental detoxification, it has been withdrawn and should be used with precaution.
The relevance of AI to the wastewater treatment industry has grown in relevance due to its capability to assist in monitoring, anomaly detection, performance prediction, optimization and decision making. The applicability of AI in chemistry and sustainable engineering was illustrated by Liu et al. (2024), who showed that the technology is particularly useful in speeding up the development of materials and energy systems design. Likewise, AI could be used to detect links between influent properties, treatment stage conditions and removal rates at WWTPs.
Mechanical and operational factors are responsible for the efficiency of treatments apart from technical and biological factors. Mechanical factors for pumps, tanks and treatment systems include flow rate, hydraulic loading, settling pattern, suspended solid concentrations, and stage stability. In the engineered systems, dynamic performance and control were crucial as stated by Hashmi et al. (2023) and it is equally applicable to wastewater treatment operation. Research in the areas of artificial intelligence, sustainability, waste management systems and chemical innovations have been emphasized in the past. However, few empirical analyses relate these fields using actual data from wastewater treatment plants. This paper is an attempt to address this issue.

3. Materials And Methods

3.1 Research Design

The research involved a quantitative statistical design that focused on testing the efficacy of wastewater treatment technology for Kanpur, Uttar Pradesh, in view of conserving the Ganga River. In doing so, the research placed emphasis on environmental monitoring, chemical pollution evaluation, wastewater technology, mechanical treatment, and sustainability assessment.

3.2 Study Area

The location for the study is Kanpur, located in Uttar Pradesh, India, which is a major urban and industrialized area, located on the banks of the river Ganga. In particular, focus was put on the facilities involved in treating wastewater such as Jajmau STP, Sajari STP, and Jajmau CETP.

3.3 Data Sources

Data collected using current water quality datasets that adhere to the CPCB/UPPCB norms for the years 2021-2025, including physicochemical and biological measurements, were used for analysis. STP/CETP data was used in the case of the treatment plants established in Kanpur, which include the 130MLD STP at Jajmau, 42MLD STP at Sajari, and 36MLD CETP

3.4 Selected Parameters

The analysis focused on four major wastewater-quality parameters:
pH was selected to assess the acidity or alkalinity of treated wastewater. It is an important indicator of chemical stability and treatment suitability. Biochemical Oxygen Demand (BOD) was chosen as an indicator of the biodegradable organic pollution. The higher the BOD value, the more oxygen microorganisms need to be able to demand the water quality and the worse it is. Chemical oxygen demand (COD) was chosen as one of the main indicators of chemical pollution as it is the oxygen consumed during the oxidation of organic and/or inorganic contaminants. Total Suspended Solids (TSS) was chosen to be measured as a solid pollutant load in treated effluent. The sedimentation, clarification efficiency and mechanical treatment performance are closely related to TSS.These parameters together give a good indicator of environmental quality, chemical pollution, the efficiency of wastewater treatment, and operational sustainability.

3.5 Data Processing

The data were preprocessed in Excel. The data cleaning procedures were: (1) to check for missing data; (2) to make formatting changes; (3) to standardize the parameter name; and (4) to format the variables selected. Data associated with Kanpur, Jajmau, Sajari, and the Ganga were kept in the main analysis.

3.6 Statistical Analysis

Mean, min, max, standard deviation, and range were calculated as descriptive statistical measures for pH, BOD, COD, and TSS values. Comparisons were made to assess the difference between the selected STPs/CETPs. To determine the relationship between the selected water quality variables, correlation analysis was applied.

3.7 Regression and Compliance Assessment

The regression analysis method was used to determine the relationship among various parameters of wastewater including COD, BOD, TSS, and pH. The values obtained were further compared to the relevant standards of wastewater quality.

3.8 Sustainability Interpretation

Conclusions were drawn with regard to sustainable wastewater management, preservation of the Ganga River, and making environmental decisions based on empirical data. As such, the study could apply the results to AI-based monitoring technologies, chemical pollution regulation, wastewater management systems' performance, and mechanics thereof.

4. Results

4.1 Dataset and Monitoring Coverage

Results have been collected from recent water quality datasets associated with the Kanpur and Ganga areas, as well as monitoring values for Sewage Treatment Plants (STPs) and Common Effluent Treatment Plants (CETPs) as shown in Table 1. Data of the river water include important Ganga monitoring stations in the Kanpur region, which are Bithoor, Ranighat, and Jajmau Bridge station. Such stations depict different levels of urban impact on the Ganga river of Kanpur. Moreover, data of treatment plants, which included 130 MLD STP Jajmau, 42 MLD STP Sajari, and 36 MLD CETP Jajmau, have also been used.

Table 1. Monitoring coverage used in the study

Monitoring component	Location/Unit	Main parameters
River-water monitoring	Bithoor, Kanpur	pH, DO, BOD
River-water monitoring	Ranighat, Kanpur	pH, DO, BOD
River-water monitoring	Jajmau Bridge, Kanpur	pH, DO, BOD
STP monitoring	130 MLD STP Jajmau	pH, BOD, COD, TSS
STP monitoring	42 MLD STP Sajari	pH, BOD, COD, TSS
CETP monitoring	36 MLD CETP Jajmau	pH, BOD, COD, TSS

4.2 Descriptive Statistics of River-Water Parameters

Based on river water measurements, it can be seen that the pH value was slightly alkaline for all three stretches of the Ganga river. The highest mean pH value was recorded in Bithoor, whereas the lowest mean pH value was recorded at Jajmau Bridge site. This shows that despite pH remaining within an acceptable alkaline level range, there were small differences in the composition of the water from each stretch as shown in Table 2. The difference in pollution levels is more evident in the BOD results. The minimum BOD value was measured at Bithoor and then in Ranighat, but the maximum mean BOD value was observed at Jajmau Bridge site.

Table 2. Descriptive statistics of Ganga monitoring locations

Station	pH mean	pH range	BOD mean (mg/L)	BOD range (mg/L)	DO mean (mg/L)
Ganga at Bithoor	8.37	8.16–8.49	3.12	3.00–3.30	8.29

Ganga at Ranighat	8.30	8.14–8.42	3.37	3.10–3.90	8.18
Ganga at Jajmau Bridge	8.20	7.96–8.36	3.98	3.80–4.40	7.53

4.3 Effluent Quality of STP/CETP Units

Comparative evaluation of the efficiency of STP and CETP has shown significant differences among the treatment facilities. The STP facility Sajari with capacity of 42 MLD had minimum BOD and COD concentration among the facilities studied, showing relatively better treatment effect as shown in Table 3. The STP facility Jajmau showed intermediate concentrations of BOD, COD, and TSS. In contrast, the CETP Jajmau was characterized by significantly higher BOD, COD, and TSS concentrations, which suggests much higher load of polluted industrial effluents being treated. Increased TSS concentration is especially important for this facility because suspended solids have a potential to carry chemicals, as well as organic substances.

Table 3. Effluent quality comparison of Kanpur STP/CETP units

Treatment unit	pH	BOD (mg/L)	COD (mg/L)	TSS (mg/L)
130 MLD STP Jajmau Kanpur	8.40	25.42	109.17	39.52
42 MLD STP Sajari	8.30	26.70	83.20	14.40
36 MLD CETP Jajmau	7.64	174.81	409.61	426.94

4.4 Comparative Interpretation

Results of comparison show that effluents of municipal secondary treatment plants (STPs) were relatively better managed compared to the effluent of the CETP. Sajari STP had the least amount of COD and TSS content, indicating better treatment of chemical load and suspended particles. COD and TSS content of Jajmau STP was high when compared to Sajari STP but was still significantly lower than those of Jajmau CETP. It is extremely important to note that the findings in respect to the CETP indicate that the BOD, COD, and TSS content were many times higher in the CETP than in any of the two STPs.

4.5 Correlation Among River-Water Parameters

There were also correlations found amongst pH, BOD, and DO in correlation analysis. For instance, there is a negative relationship between BOD and DO since the more the amount of organic pollutants, the less DO will be available in the river water as shown in Table 4. In other words, it was discovered that high BOD can lead to low DO in the river water. These findings are very important from an environmental point of view because the availability of oxygen in the river water is critical both for organisms living in it and for the natural purification process.

Table 4. Correlation matrix of key river-water parameters

Parameter	pH	BOD	DO
pH	1.000	-0.560	0.576
BOD	-0.560	1.000	-0.375
DO	0.576	-0.375	1.000

4.6 Regression-Based Interpretation

From a regression-based point of view, it appears reasonable to use biochemical oxygen demand (BOD) as the key measure of pollution pressure for the Kanpur portion of the Ganga River. With increasing BOD, there is likely to be a decline in dissolved oxygen levels, suggesting that the pollution with organics affects the balance of oxygen in the river. Just like BOD, the higher figures of chemical oxygen demand (COD) and total suspended solids (TSS) coming out of the treatment plants represent the pressure of chemical and mechanical treatment measures, respectively. Therefore, it seems sensible to use these factors when assessing treatment effectiveness.

4.7 Compliance-Oriented Assessment

The compliance-oriented approach clearly shows better functioning of the STPs than the CETP. The Sajari STP of 42 MLD was found to be the highest-performing unit with regard to COD and TSS. The STP Jajmau of 130 MLD was also found to be performing moderately well, but still, there is need for continuous monitorin as shown in Table 5. The CETP Jajmau of 36 MLD needs special attention because of higher values of BOD, COD, and TSS. It can thus be concluded that treatment of wastewater from industries is quite challenging.

Table 5. Compliance-oriented interpretation of treatment units

Unit	Result interpretation
130 MLD STP Jajmau	Moderate effluent quality; regular COD and TSS monitoring required
42 MLD STP Sajari	Best overall effluent quality among selected units
36 MLD CETP Jajmau	Critical pollution-sensitive unit due to high BOD, COD, and TSS

All things considered, it can be stated that BOD, COD, and TSS turn out to be the most important factors in analyzing wastewater treatment quality in Kanpur. Data on river monitoring suggest that the pollution pressure from the organic viewpoint at the Jajmau Bridge is higher than at Bithoor and Ranighat. Based on the analysis of the treatment unit, municipal Sewage Treatment Plants (STPs) prove superior to the Jajmau CETP; yet, the latter proves to be the most critical point for controlling pollution. The presented findings confirm the main statement of the article in that a sustainable approach to wastewater management requires the integration of several fields.

5. Discussion

Based on the results, it can be said that the water quality of Kanpur is highly affected by the discharge of municipal waste into the river and the efficiency of the treatment plants. The high level of BOD seen in the area near the Jajmau Bridge relative to the two other stations implies that the downstream area of the Ganga River has to cope with a higher level of pollution than the other two areas.

The findings show that there is significant variance in the effectiveness of waste water treatment between the two facilities. For example, the 42 MLD STP Sajari shows a relatively higher degree of efficiency for effluents, specifically with regard to COD and TSS, but the 36 MLD CETP Jajmau has much higher levels of BOD, COD, and TSS. In such circumstances, industrial wastewater treatment poses a big problem for the Kanpur-Ganga area. The high COD level indicates a presence of pollutants that can be treated through chemical oxidation, while high TSS values indicate inefficiency in eliminating solid particles or heavy particulate pollution. Advanced materials and their environmental detoxifying potential have been mentioned as an issue related to the treatment of such pollutants, although the research by Sharma et al. (2022) must be used with some reservation because of retraction.

This study is centered on the environmental and chemical significance of pH, BOD, COD, TSS, and DO. BOD and COD levels offered more convincing proof of pollution stress, although pH stayed in a slightly alkaline range, indicating no excessive acidity or alkalinity. Because COD represents a chemical load that extends beyond biodegradable organic matter, it is particularly significant for industrial wastewater. From the standpoint of mechanical treatment, TSS is similarly significant since suspended-solid removal is directly impacted by settling, clarifying, and filtration efficiency. Contaminant removal technologies, such as layered composites and designed adsorbents, have also been emphasized as helpful for controlling water pollution (Yu et al., 2018).

The difference between STP and CETP performance from a mechanical and operational standpoint indicates that treatment effectiveness is dependent on hydraulic loading, aeration, settling behavior, sludge handling, and process control in addition to pollutant load. Wastewater systems' operational complexity is comparable to that of other designed infrastructure systems, where sustainable operation depends on planning, optimization, and performance control (Theo et al., 2017).

The findings provide more evidence for the use of AI and data-driven monitoring in wastewater treatment. The observed connections between BOD, DO, COD, and TSS indicate that these datasets can enable future predictive modeling, even though the current study employed Excel-based statistical analysis. AI-based techniques have already been acknowledged for decision assistance, anomaly detection, wastewater monitoring, and treatment optimization (Safer et al., 2022; Yang et al., 2025). As a result, the current results offer a statistical basis for upcoming AI-enabled wastewater infrastructure monitoring in Kanpur.

Additionally, the findings is consistent with modern sustainability literature that emphasizes waste reduction, resource efficiency, and circularity. While Shahar et al. (2025) and Wang and Shi (2025) stressed the necessity of turning waste-related problems into sustainable material and biological solutions, Rowan (2023) emphasized the significance of circularity in environmental systems. By lowering pollution discharge into the Ganga River and enhancing urban water governance, better wastewater treatment in Kanpur can help achieve Namami Gange goals.

The study does have several drawbacks, though. The research does not offer sophisticated machine-learning prediction or real-time anomaly identification because it was based on readily available monitoring datasets and Excel-based statistical tools. Larger time-series datasets, sensor-based monitoring, and AI/ML models should be used in future studies to more precisely forecast COD, BOD, TSS, and compliance risk.

6. Conclusion

This study shows that environmental monitoring, chemical pollution assessment, wastewater-treatment engineering, mechanical infrastructure operation, and AI-oriented data interpretation must all be applied in tandem for sustainable wastewater management. Using the recent datasets correlated with the river Kanpur and Ganga, important river water quality and treatment unit parameters such as pH, BOD, COD, TSS and DO were assessed in the study to understand the performance and river water quality. Comparison of STP/CETP showed that the problem of the treatment of industrial effluent is still a major issue particularly in the presence of high BOD, COD and TSS. The findings also revealed that the effects of pollution pressure were more evident near Jajmau stretch. The study highlights that the local wastewater data sets are more contextually relevant and accurate than generalized data sets in the past since the data sets provide a better depiction of the conditions of Kanpur wastewater and its connection to Ganga River conservation. The results are also helpful for policy as they report key monitoring points, treatment performance differences and if the results are not in line with treatment, further compliance-driven management. The present work provides a valuable foundation for wastewater monitoring based on Artificial Intelligence, but not with advanced machine-learning modelling, but by means of statistical analysis. For future studies, the use of larger real-time datasets and predictive AI models can be leveraged to improve pollution forecasting, anomaly detection, and sustainable wastewater decision-making.

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