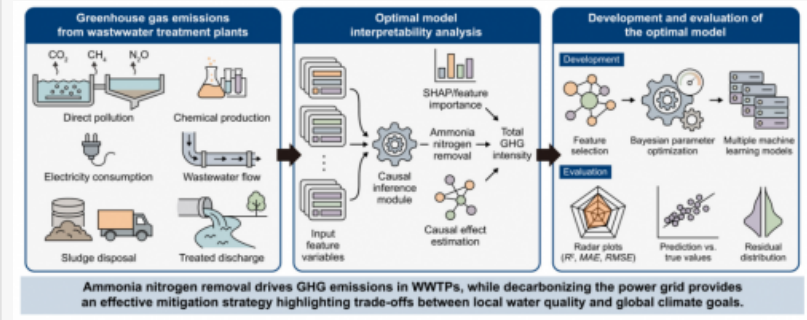
Causal direct drivers of greenhouse gas emissions in 40,722 wastewater treatment plants in China



Causal drivers of wastewater treatment emissions.

FAYETTEVILLE, GA, UNITED STATES, June 5, 2026 /EINPresswire.com/ -- Wastewater treatment protects rivers, cities, and public health, but it also carries a hidden climate cost. A large-scale study of 40,722 wastewater treatment plants (WWTPs) in China shows that efforts to meet stricter discharge standards can raise greenhouse gas (GHG) emissions, especially when deeper nitrogen removal requires more energy and chemicals. By combining interpretable machine learning (IML) with causal inference, the study identifies ammonia nitrogen (NH□-N) removal as the strongest direct driver of total greenhouse gas emission intensity (GEI). It also shows that decarbonizing regional power grids could substantially offset these emissions, offering a practical path to balance cleaner water with lower carbon impacts.

Wastewater treatment plants (WWTPs) are essential infrastructure, yet they consume large amounts of energy and generate emissions through biological treatment, electricity use, chemical production, sludge handling, and residual pollutants released with treated discharge. Previous studies have often described correlations between plant operations and emissions, but many could not clearly separate true causal drivers from intermediate factors such as electricity consumption, chemical dosing, or sludge yield. This makes it difficult to decide whether emissions should be reduced through process optimization, cleaner electricity, revised standards, or coordinated policy design. Based on these challenges, deeper research is needed to identify the causal mechanisms linking wastewater treatment performance, operational demand, and carbon emissions.

A research team from the State Key Laboratory of Urban Water Resource and Environment and the School of Environment, Harbin Institute of Technology, China, conducted the study, which was accepted (DOI: 10.1016/j.ese.2026.100709) on May 16, 2026, and will appear in Environmental Science and Ecotechnology. The article uses national operational data from 2009 to 2019 to reveal how discharge standards, nitrogen removal, and regional electricity-grid carbon

intensity jointly shape the climate footprint of wastewater treatment.

The researchers built an integrated framework that combined greenhouse gas accounting, structural equation modeling (SEM), feature selection, machine-learning prediction, model interpretation, and causal-effect estimation. They first estimated emissions from four main sources: direct process emissions, indirect emissions from electricity and chemical production, sludge treatment and disposal, and downstream emissions from treated discharge. SEM was then used to exclude mediator variables, including electricity consumption, sludge yield, sodium acetate use, and polyaluminum chloride consumption, allowing the model to focus on more fundamental direct drivers. After comparing four feature-selection methods and ten machine-learning algorithms, random forest (RF) provided the strongest model for total gas emission intensity (GEI). Shapley additive explanations (SHAP) identified NH□-N removal, electricity emission factor (EF), Class 1A discharge standard, influent total nitrogen (TN), and year as major contributors. Causal analysis showed that a 10% increase in NH□-N removal raised total GEI by 5.65%, while a 10% reduction in regional electricity EF produced a 4.45% equivalent reduction. These results reveal a sharp trade-off: stricter nitrogen removal improves effluent quality but can increase carbon emissions, whereas cleaner power grids can reduce the climate burden without weakening wastewater treatment performance.

The authors said the findings show that low-carbon wastewater management cannot rely on a single technical adjustment inside treatment plants. Instead, they said, the study reveals a connected system in which discharge standards, influent water quality, biological nitrogen removal, chemical use, sludge handling, and regional power generation all shape emissions. In their view, the most useful contribution is not only identifying NH□-N removal as a dominant driver, but also showing that power-grid decarbonization can serve as a powerful and realistic mitigation lever.

The study provides a decision-making framework for wastewater policies that protect both water quality and the climate. For plant operators, it highlights the need to optimize nitrogen removal, external carbon addition, and sludge management with carbon costs in mind. For regulators, it suggests that future discharge standards should evaluate ecological benefits together with greenhouse gas (GHG) impacts and economic feasibility. For energy and water planners, the results show that wastewater-sector decarbonization is closely tied to regional electricity transitions. As countries upgrade wastewater infrastructure, this causal framework could help identify where stricter treatment, cleaner power, and process optimization can work together rather than pull in opposite directions.

References
DOI
10.1016/j.ese.2026.100709

Original Source URL
https://doi.org/10.1016/j.ese.2026.100709

Funding Information
This research was supported by the Jing-Jin-Ji Regional Integrated Environmental Improvement-National Science and Technology Major Project (2025ZD1203900).

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