

Executive Summary

- This study develops an intelligent supervised machine learning prediction model to estimate and compare life-cycle costs of Open-Cut Pipeline Installation (OCPI) and trenchless CIPP Renewal Technology for wastewater system rehabilitation.
- The model integrates Construction, Environmental, and Social Cost components to evaluate the total cost per linear foot across sewer pipe diameters of 6–84 inches.
- Although preliminary cost comparison studies exist, no validated ML-based model has been developed to predict and compare life-cycle costs between OCPI and CIPP across this full diameter range.
- This decision-making tool will enable engineers and municipalities to select the most cost-effective and sustainable rehabilitation method based on the entire service life of the pipeline.

Introduction and Background

- The 2021 report card for America's Infrastructure by the American Society of Civil Engineers (ASCE) has assigned a D+ grade to the condition of U.S. wastewater infrastructure.
- The national wastewater footprint includes over 800,000 miles of public sewers and an additional 500,000 miles of private lateral sewers connecting homes and businesses to public lines (EPA 2024). Much of this network is 50–100 years old, making it increasingly susceptible to pipe collapses, blockages, and sanitary sewer overflows.
- Renewal and replacement of these deteriorating pipelines is a significant obstacle faced by municipalities, with only 40% employing formal cost estimation methods for rehabilitation planning.
- Conventional Open-Cut Pipeline Installation (OCPI) requires full reinstatement of ground surfaces such as sidewalks, pavement, and landscaping, imposing negative impacts on communities, businesses, and commuters due to surface and traffic disruptions.
- Trenchless CIPP Renewal Technology places a structural liner within the existing pipe without excavation, offering a viable alternative with reduced cost, time, and surface disruption compared to traditional open-cut methods.

Method and Scope

- This research introduces a comprehensive Life Cycle Cost Analysis (LCCA) framework that combines supervised machine learning, environmental impact modeling, and bibliometric analysis to evaluate and compare OCPI and CIPP Renewal Technology. The main goal is to develop a predictive model using four supervised ML algorithms to estimate construction, environmental, and social costs per linear foot. The study covers sanitary sewer pipes with diameters ranging from 6 to 84 inches across four categories using an 80/20 stratified train-test split for model validation.
- Table 1 shows the scope of the work.

Table 1. Scope of work

Attribute	Description	Included in Study	Not Included in Study
Installation Methods	Sewer pipeline installation or renewal technique	OCPI and CIPP	Other trenchless methods (e.g., pipe bursting, slip lining)
Cost-affecting Factors	Different factors affecting the cost of sewer pipes	Pipe Diameter, Liner Thickness, Host Pipe Length, Letting Year, Location, Bid Price (Cost), Excavation Depth	Effect of water table, different soil conditions, pipe material
Cost Components	Types of life-cycle cost components analyzed	Construction, Environmental, and Social Costs	Residual, maintenance, and replacement costs
Project Data	Source and scale of project records	750+ projects across the U.S.	International datasets
Diameter Range	Internal pipe diameter considered in cost modeling	6–84 in.	Pipes smaller than 6 in. or larger than 84 in.
Resin Type and Curing Method	For CIPP, the type of resin and curing method used	Alpha Owens Corning L010-PPA-38 Vinyl Ester, and Steam Curing	Different types of resin, liner, and curing methods are excluded
Service Type	Nature of sewerage network studied	Sanitary and storm sewers	Stormwater and combined sewer systems
LCCA Standard Applied	Framework used to define life-cycle cost analysis	ASTM C1131-20 standard	ISO 15686, EN 12973, or other regional LCCA standards
Environmental Modeling	LCA methodology used to estimate emissions	ReCiPe 2016 of SimaPro software	GaBi, Umberto, or other proprietary tools

Results and Analysis

- A scientometric study leveraging VOSViewer software offers valuable insights into the core research themes in this field. Keywords serve as indicators of the primary areas of interest within a given research domain.
- Overall, visualization captures a progression from traditional engineering principles to the adoption of sustainable approaches in contemporary research and practice (Figures 1 and 2). Figure 2 is a network visualization with a gradient bar showing the timeline from 2010 to 2025, highlighting the evolution of research focus and emerging areas in the field.

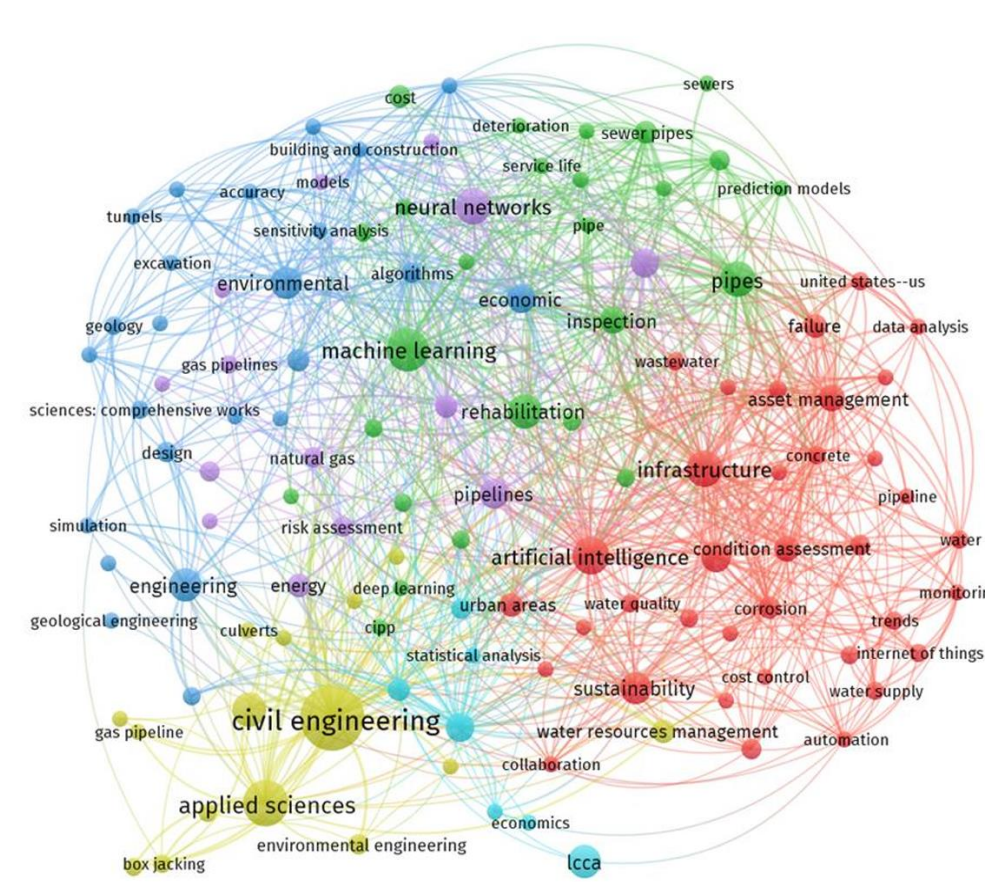


Figure 1. Visualization Capture

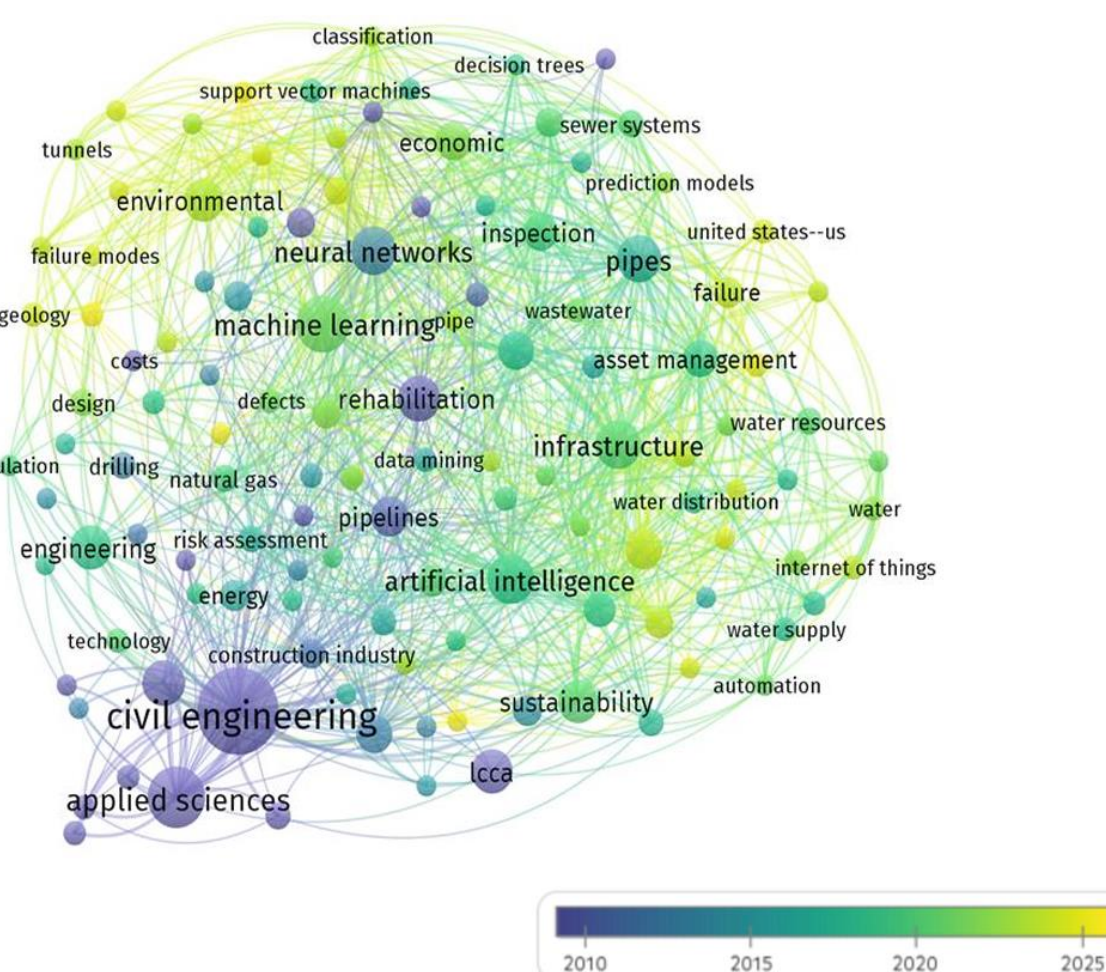


Figure 2. Visualization Capture

- This study used a triangulated approach to compile data, integrating real-life case studies, contractor bid tabulations, and peer-reviewed literature across more than 750 pipeline installations in the United States, normalized to 2025 USD.
- Robust ML models require high-quality, structured data. However, raw datasets from diverse sources often have inconsistencies, incompleteness, and non-uniform formats. A rigorous preprocessing pipeline using Multiple Imputation by Chained Equations (MICE), outlier removal, and stratified 80/20 partitioning was implemented to ensure data reliability and analytical readiness.

Discussion and Conclusions

- To address these challenges, a rigorous data preparation pipeline was implemented. The dataset compiled for this research includes more than 750 pipeline installation records pertaining to OCPI and CIPP Renewal Technology for sanitary sewers across various U.S. states, normalized to 2025 USD.
- The results of the data collected and divided into diameter categories are shown in Figure 3, demonstrating that CIPP LCC values are on average ~56% lower than OCPI, with the greatest savings occurring in small to large diameter ranges (6–60 in.).
- CIPP enables approximately 2.3x more rehabilitated length per dollar than OCPI when CC, EC, and SC are fully internalized. For OCPI, CC contributes >85% of total LCC, driven by excavation, shoring, and hauling. For CIPP, CC accounts for ~56% at small and ~80% at very large diameters; SC $\approx$ 2.26 \$/ft (<2% of LCC).

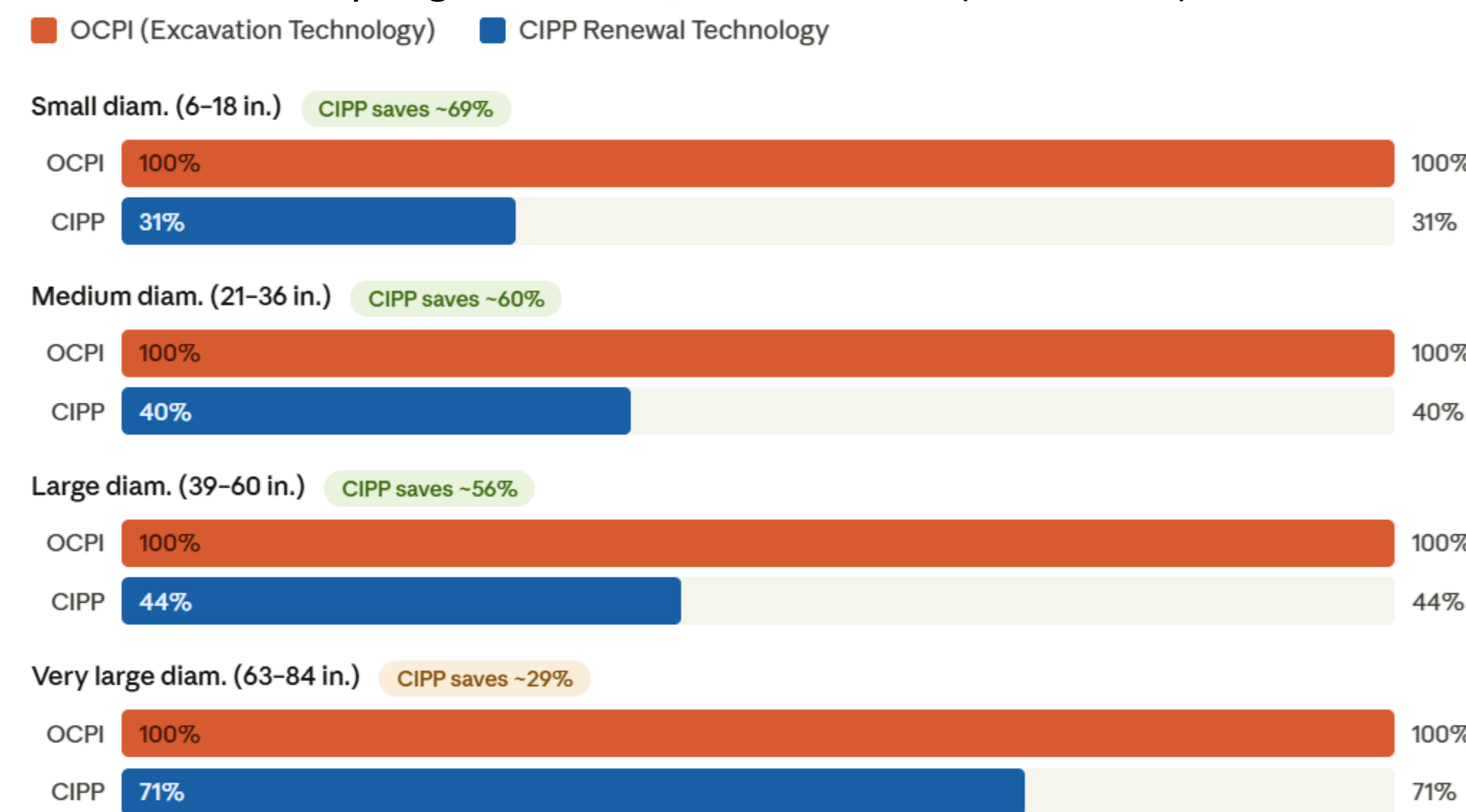


Figure 3. Results and Findings

Future Research Recommendations

- Based on the conclusions and findings of this study, the following recommendations are for future research to extend the environmental impact assessment of OCPI and CIPP Renewal Technology, focusing on several key areas.
- The research conducted had limitations in specific working environments, pipe materials, curing methods, resin types, and diameter sizes examined for the environmental impact of OCPI and CIPP Renewal Technology.
- Expanding the analysis to different geographic and working environments will provide deeper insight into regional cost variations and emission profiles across the full diameter range.
- Research should also extend the Social Cost evaluation to include a broader range of community impact variables, and comparisons of OCPI with other trenchless rehabilitation methods are necessary to explore sustainable alternatives.
- Finally, adopting advanced testing methodologies will help detect any unidentified harmful substances released during the CIPP curing process, supporting safer and more environmentally responsible implementation.

References

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