

Investigating Sewer Corrosion Drivers Using Quantitative Modeling

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ABSTRACT: The corrosion of concrete sewers presents a serious challenge to urban infrastructure, threatening the structural integrity and operational efficiency of wastewater systems worldwide. Corrosion occurs through chemical and biological reactions, where the formation of sulfuric acid due to microbial activity leads to progressive deterioration of concrete surfaces, ultimately weakening the material and accelerating failure. This degradation increases maintenance costs, shortens infrastructure lifespan, and poses risks to public health and environmental safety. Despite extensive research on sewer corrosion, most studies focus on individual factors rather than conducting a comprehensive assessment of all contributing factors. This study addresses this gap by systematically identifying and evaluating the most influential factors driving sewer corrosion. A multi-step methodology was employed, including a literature review to identify key sewer corrosion drivers (SCDs), an expert survey targeting professionals in infrastructure and environmental engineering, and a statistical analysis of the collected data. The findings were further validated using Partial Least Squares Structural Equation Modeling (PLS-SEM) to establish relationships between these factors. The results indicate that environmental drivers (ED) exert the strongest influence on sewer corrosion, followed by operational drivers (OD) and, finally, pipe-related drivers (PRD). These findings offer practical implications for infrastructure engineers, policymakers, and wastewater management agencies by guiding preventive maintenance strategies, optimizing material selection, and improving sewer system design. By implementing these insights, municipalities can enhance the resilience of wastewater infrastructure, minimize unexpected failures, and promote sustainable urban development.

Keywords: Sewer corrosion factors - Infrastructure resilience - Partial Least Squares-Structural Equation Modeling (PLS-SEM) - Environmental decision-making

1. INTRODUCTION

Sewer systems are crucial to urban infrastructure, transporting over 95% of household, industrial, and urban waste (Pramanik et al., 2024). Despite their importance, their underground nature often leads to underestimated maintenance needs. Countries like Singapore, Qatar, and the UK have invested in large-scale sewer projects, designed to last over 100 years (Anwar et al., 2022). Concrete is widely used in sewage systems worldwide because of its durability and cost-effectiveness; however, it is also more susceptible to biogenic corrosion compared to other pipe materials (Pramanik et al., 2024). Reinforced concrete sewers face significant corrosion challenges. This complex biochemical process involves H₂S production by sulfate-reducing bacteria (SRB), its release into the sewer atmosphere, oxidation into sulfuric acid by sulfur-oxidizing bacteria (SOB), and subsequent chemical attacks on concrete surfaces (Pramanik

et al., 2024). Despite extensive research on sewer corrosion mechanisms, the field remains complex and contested due to the multifaceted interactions among contributing factors and the absence of universally accepted assessment methodologies (Luimes et al., 2022). This lack of clarity poses a major challenge for urban planners and utility managers, who must make costly decisions about inspection, repair, and rehabilitation with limited understanding of what drives sewer deterioration in real-world settings. Sewer corrosion is influenced by a combination of operational drivers (OD), environmental drivers (ED), and pipe-related drivers (PRD), as detailed in Table 1. Previous studies have predominantly relied on laboratory and field tests to assess the effects of individual factors on corrosion. While these methods offer valuable insights, they are constrained by their inability to replicate real-world sewer environments' intricate, dynamic conditions accurately. Furthermore, the focus on isolated variables limits the scope of these studies, preventing a comprehensive understanding of how multiple, interacting factors collectively influence corrosion processes. This fragmented approach has led to significant gaps in the holistic understanding of sewer corrosion dynamics. Motivated by the urgent need for more integrated and practically applicable insights into sewer corrosion, the present study aims to systematically analyze the influence of various causative factors on sewer corrosion by incorporating expert perspectives and employing advanced statistical techniques, such as Partial Least Squares Structural Equation Modeling (PLS-SEM). This approach allows for modeling the complexity of real-world conditions more effectively than traditional methods, addressing both direct and indirect relationships among drivers. The outcomes of this research are expected to provide actionable insights for infrastructure and environmental engineers, enhancing decision-making in the design, operation, and maintenance of sewer networks. In particular, the study aims to identify key intervention points where targeted strategies can significantly extend asset lifespan and reduce lifecycle costs. By identifying and prioritizing the most influential corrosion drivers, this study will contribute to developing strategies that mitigate corrosion risks, improve the durability of sewer infrastructure, and reduce long-term maintenance costs. Ultimately, this work supports the broader goal of building more resilient and sustainable urban water systems.

2. RESEARCH METHODOLOGY

This study follows a four-stage methodology, as illustrated in Figure 1. The stages include: (1) a comprehensive literature review to systematically identify and categorize the most critical sewer corrosion drivers (SCDs); (2) the design and pilot testing of a questionnaire to evaluate the clarity, relevance, and significance of SCDs in sewer systems; (3) the statistical analysis of questionnaire results, where the mean and standard deviation (SD) of respondents' answers were calculated to determine the ranking and significance of the factors; and (4) the application of PLS-SEM to analyze the relationships between SCDs and sewer systems corrosion.

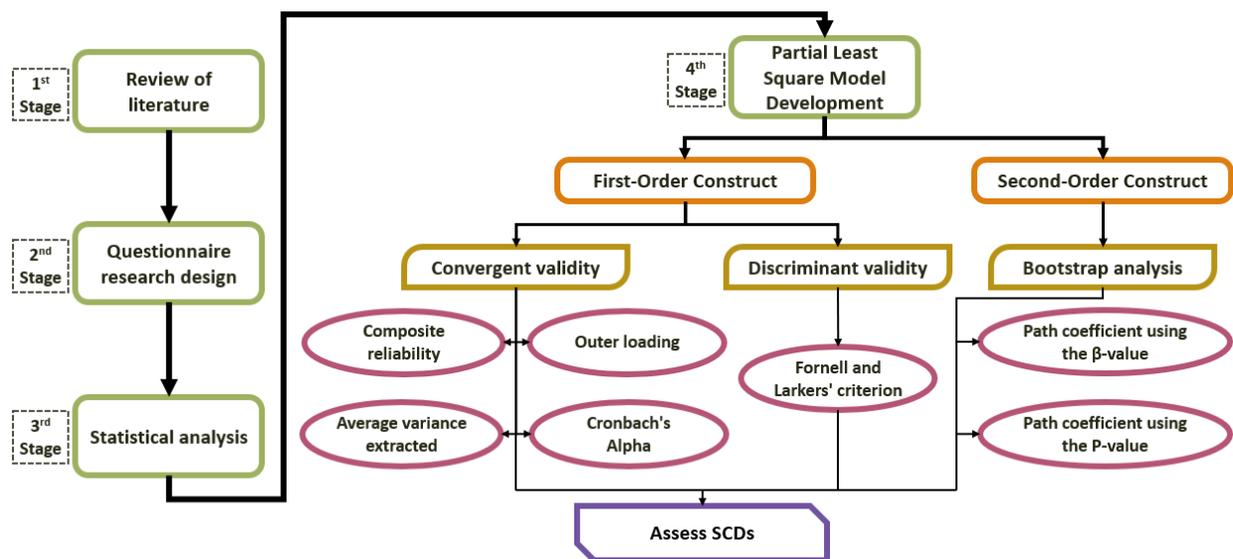


Figure 1: Research methodology

2.1 Literature-Based Exploration of Sewer Corrosion Drivers

This study employed an extensive literature review to identify and evaluate the SCDs systematically (Ibrahim, Abdelkhalik, et al., 2024; Ibrahim, Faris, et al., 2024). Academic databases such as Scopus and Web of Science were utilized to gather relevant literature. Drawing on methodologies from prior studies (Elrifaae et al., 2024; Ibrahim et al., 2025). Additionally, the classification of SCDs into categories was based on the approach outlined in (Hussein Farh et al., 2023). The identified SCDs are summarized in Table 1.

Table 1: List of SCDs with their relevant coding system.

Code	Driver	References	Code	Driver	References
OD1	Sulfate in wastewater	(Silamat et al., 2024)	ED6	Drying-Wetting Cycle	(Sun et al., 2015)
OD2	Wastewater Temperature	(Anwar et al., 2022)	ED7	SOB in Sewer Airgap	(Jensen et al., 2011)
OD3	pH of wastewater	(Sharma et al., 2013)	ED8	Ventilation Condition	(Anwar et al., 2022)
OD4	SRB in wastewater	(Lors et al., 2018)	ED9	Climatic Conditions	(Zuo et al., 2019)
OD5	Dissolved H ₂ S	(Anwar et al., 2022)	ED10	External Loads	(Zamanian & Shafieezadeh, 2023)
OD6	BOD*	(Pramanik et al., 2024)	ED11	Land Use	(Burant et al., 2018)
OD7	Dissolved Oxygen (DO)	(Kunetz et al., 2024)	ED12	Soil Properties	(He & Koizumi, 2013)
OD8	Salinity of wastewater	(Zhou et al., 2021)	ED13	Groundwater Properties	(Qualit et al., 2012)
OD9	ORP**	(Kunetz et al., 2024)	PRD1	Length of Pipe	(Liang et al., 2019)
OD10	Deposits	(Pang et al., 2023)	PRD2	Diameter of Pipe	(Luimes et al., 2022)
OD11	Cracks in sewer	(Wang et al., 2023)	PRD3	Age of Pipes	(Hong et al., 2024)
OD12	Fats, Oils, and Grease	(Franke et al., 2011)	PRD4	Cover Thickness	(Jin et al., 2024)
OD13	Turbulence (Flow Velocity)	(Zuo et al., 2021)	PRD5	Pipe Fullness Percentage	(Kong et al., 2021)
OD14	Retention Time (RT)	(Matias et al., 2017)	PRD6	Concrete Alkalinity	(Wan et al., 2021)
ED1	Sewer Airgap Temperature	(Jiang et al., 2014)	PRD7	Concrete Porosity	(Zhang et al., 2018)
ED2	H ₂ S (Gas)	(Sun et al., 2019)	PRD8	Type of Cement	(Khan et al., 2019)
ED3	Sulfuric Acid (H ₂ SO ₄)	(Mahmoodian & Alani, 2017)	PRD9	Geopolymer	(Grenng et al., 2020)
ED4	Relative Humidity (RH%)	(Pramanik et al., 2024)	PRD10	Polymer Modified Cement	(Pramanik et al., 2024)
ED5	CO ₂ (Gas)	(Ling et al., 2014)	PRD11	Supplementary Cement Products	(Pramanik et al., 2024)

*BOD: Biochemical Oxygen Demand; **ORP: Oxidation-Reduction Potential.

2.2 Questionnaire Research Design

A pilot study was initially conducted to evaluate the clarity, relevance, and completeness of the questionnaire. While a minimum of 10 participants is typically recommended (Ali et al., 2023b), feedback was gathered from 16 experts—11 industry professionals and 5 academics, each with over 10 years of experience in sewer system management and corrosion studies. Their input helped refine question wording, eliminate ambiguities, and validate the list of SCDs. The pilot results indicated excellent reliability, with a Cronbach's alpha coefficient of 0.91. The finalized questionnaire was structured into 3 sections. The first section gathered demographic and professional background information from respondents. The second focused on identifying factors influencing the corrosion of concrete sewers. The final section featured an open-ended question, inviting additional insights on factors relevant to sewer corrosion. A 5-point Likert scale was used to assess the effectiveness of specific SCDs, where 5 indicated very effective and 1 signified not effective at all (Ali et al., 2023b). The questionnaire was distributed to sanitation professionals across China and Hong Kong through various professional networks. Participants were prequalified based on two criteria: (1) holding at least a bachelor's degree in civil engineering, environmental science, or a related field, and (2) possessing a minimum of five years of relevant experience in sanitation, sewer systems, or environmental management as practitioners or researchers. For Structural Equation Modeling (SEM) analysis, a minimum of 100 responses is recommended (Ali et al., 2023b). This study successfully collected 125 valid responses, meeting the required sample size for SEM. The demographic profile of respondents reveals that the majority (57%) have 11–15 years of experience, followed by 30% with 5–10 years, and 13% with 16 years or more. Regarding job roles, 30% of respondents are Environmental Engineers, while 23% are Researchers/Scientists. Additionally, 17% are Wastewater Treatment

Specialists, 14% are Sewer Maintenance Technicians, 9% are Infrastructure Consultants, and 7% are Project Managers. This diverse expertise ensures a well-rounded perspective on sewer corrosion, enhancing the study's reliability and applicability. This questionnaire does not require ethics committee approval as it does not involve human experiments, but all measures were taken to ensure confidentiality, integrity, and transparency.

2.3 Statistical analysis

The statistical mean is a key measure for assessing central tendency, especially in studies using a grading scale (Hwang et al., 2018). The mean consolidates responses, offering a quantitative representation of each driver's significance. In a 5-point Likert scale, a threshold of 3.50 is commonly used to distinguish between 'moderately significant' (3.0) and 'highly significant' (4.0) factors (Wuni & Shen, 2020). Therefore, drivers with mean scores above 3.50 are considered more aligned with high significance. The standard deviation (SD) further complements the mean by reflecting response consistency, ensuring a robust evaluation of critical factors (Wuni & Shen, 2022). The statistical analysis commences with the calculation of the mean of the factors, utilizing the mean formula specified in "Eq. 1" (Wuni et al., 2022).

$$[1] M = \frac{\sum(X \times F)}{T}, (1 \leq M \leq 5)$$

The mean score (M) quantifies expert assessments on a 5-point scale, where X represents the assigned score (ranging from 1 = Very Low to 5 = Very High significance), F denotes the frequency of each score, and T is the total number of responses for a given factor.

2.4 Partial Least Square Model Development

Structural Equation Modeling (SEM) is employed to validate causal relationships between constructs, analyzing both direct and indirect effects. In this study, SEM follows a two-stage process: first, the evaluation of the measurement model for first-order constructs, and second, the assessment of the measurement model for second-order constructs. The Partial Least Squares SEM (PLS-SEM) approach was chosen for its superior predictive accuracy, ability to handle complex models with multiple constructs, and its effectiveness in explaining experimental variance compared to covariance-based SEM (Hair et al., 2019).

2.4.1 Measurement Model (First-Order Construct)

The measurement model for first-order constructs was assessed through tests of convergent and discriminant validity. Convergent validity was evaluated using outer loadings, composite reliability (ρ_c), Cronbach's Alpha (α), and average variance extracted (AVE). Outer loadings represent the correlation between indicators and their constructs, with values of 0.7 or higher considered ideal, although loadings above 0.5 are acceptable in exploratory research (Ali et al., 2023a). Composite reliability, a more accurate measure of internal consistency than Cronbach's Alpha, accounts for the varying factor loadings of indicators. ρ_c values above 0.8 indicate good reliability, while values of 0.9 or higher reflect excellent reliability (Hock et al., 2010). Cronbach's Alpha, though commonly used, assumes equal weighting of indicators and is considered acceptable when exceeding 0.6 (Hock et al., 2010). The AVE assesses how much variance in the indicators is captured by the latent construct relative to measurement error, with values greater than 0.5 confirming sufficient convergent validity (Ali et al., 2023b).

Discriminant validity was tested using Fornell and Larcker's Criterion. Fornell and Larcker's Criterion compares the square root of a construct's AVE with its correlations to other constructs, confirming discriminant validity when the AVE square root exceeds these correlations (Ali et al., 2023b). All statistical computations, including ρ_c , Cronbach's Alpha, and AVE, were conducted using SmartPLS software, which improves accuracy, minimizes computational errors, and provides visual outputs that enhance the interpretation of results.

2.4.2 Measurement Model (Second-Order Construct)

The measurement model for second-order constructs involved analyzing higher-level latent variables represented by their associated first-order constructs. The contribution of each second-order construct was evaluated using bootstrap analysis, a resampling technique that estimates the significance of relationships by providing accurate standard errors and confidence intervals (Hair et al., 2019). This analysis focused on two components: the β -value and the p-value. The β -value measures the strength of relationships between constructs, with values greater than 0.09 indicating acceptable effects and higher values signifying stronger relationships (Ali et al., 2023b). The p-value determines the statistical significance of path coefficients, with values of 0.05 or lower considered significant (Ali et al., 2023a).

3. RESULTS

3.1 Statistical Analysis

The statistical analysis results indicate that all factors hold significant importance, as the mean values for all factors exceed 3.5, as shown in Table 2. Additionally, the standard deviation values reveal that most are below 1, suggesting a high level of agreement among participants. While a few values exceed a standard deviation of 1, the highest recorded value is 1.125, which remains within an acceptable range and reflects natural variability in opinions. The factors were ranked both within their respective categories and in an overall ranking. In cases where two or more factors had the same mean value, the ranking was determined by comparing their standard deviation values, with the factor having the lower standard deviation placed higher.

Table 2: Ranking of SCDs based on statistical analysis.

Driver Code	Mean	SD	Category Rank	Overall Rank	Driver Code	Mean	SD	Category Rank	Overall Rank
Operational Drivers (OD)									
OD1	3.704	1.024	3	6	ED6	3.648	1.026	6	17
OD2	3.696	0.863	4	7	ED7	3.704	0.916	3	5
OD3	3.68	0.894	6	10	ED8	3.552	0.920	8	29
OD4	3.728	0.945	2	4	ED9	3.56	0.745	7	26
OD5	3.776	0.869	1	2	ED10	3.512	0.867	12	37
OD6	3.688	1.125	5	9	ED11	3.504	0.972	13	38
OD7	3.672	1.046	7	13	ED12	3.536	0.903	10	33
OD8	3.608	0.958	11	22	ED13	3.528	0.779	11	35
OD9	3.648	0.909	9	16	Pipe-Related Drivers (PRD)				
OD10	3.576	0.961	12	24	PRD1	3.648	0.891	2	15
OD11	3.56	0.902	13	27	PRD2	3.632	0.866	3	18
OD12	3.552	1.027	14	30	PRD3	3.672	0.878	1	11
OD13	3.656	1.048	8	14	PRD4	3.552	0.866	8	28
OD14	3.616	0.896	10	20	PRD5	3.536	0.980	10	34
Environment Drivers (ED)									
ED1	3.688	1.050	4	8	PRD6	3.608	0.879	5	21
ED2	3.776	0.941	2	3	PRD7	3.592	0.862	6	23
ED3	3.792	1.057	1	1	PRD8	3.568	0.797	7	25
ED4	3.672	1.038	5	12	PRD9	3.616	0.878	4	19
ED5	3.544	0.963	9	31	PRD10	3.544	1.012	9	32
					PRD11	3.512	0.819	11	36

3.2 Measurement (First-Order Construct)

The assessment of convergent validity confirms the reliability and consistency of the measurement model. As illustrated in Figure 2, the outer loadings of several indicators exceed the recommended threshold of 0.7, specifically ED1, ED4, ED5, ED8, ED9, ED10, OD6, OD10, PRD1, PRD3, PRD4, PRD6, PRD8, and PRD11, indicating strong reliability. Meanwhile, other indicators, including ED2, ED3, ED6, ED7, ED11, ED12, ED13, OD1, OD2, OD3, OD4, OD5, OD7, OD8, OD9, OD11, OD12, OD13, OD14, PRD2, PRD5,

PRD7, PRD9, and PRD10, exhibit outer loadings above 0.6, which, although lower, still fall within the acceptable range. Further reinforcing the model's reliability, the Composite Reliability (ρ_c) values for all constructs surpass the required threshold of 0.9, as depicted in Figure 2, demonstrating excellent internal consistency. Likewise, Cronbach's Alpha (α) for all constructs exceeds the minimum acceptable threshold of 0.6, confirming strong internal reliability across the measurement model. Additionally, the Average Variance Extracted (AVE) for all constructs is above the required threshold of 0.5, as presented in Figure 2, ensuring that each construct captures sufficient variance from its indicators. This rigorous evaluation of convergent validity provides strong empirical support for the theoretical framework, reinforcing the credibility and applicability of the model.

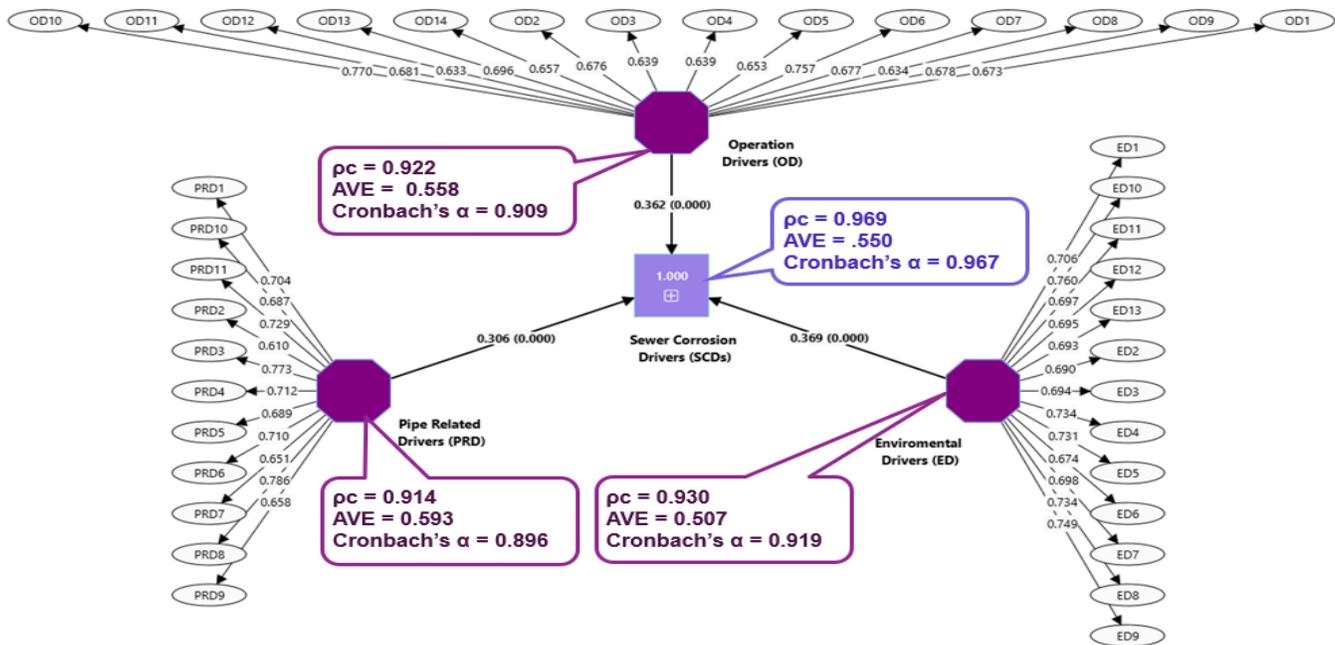


Figure 2: PLS-SEM Model.

Beyond convergent validity, discriminant validity further ensures that each construct is unique and does not excessively overlap with others. The Fornell and Larcker criterion, as displayed in Table 3, confirms this distinction by demonstrating that the correlation of each construct with itself is higher than its correlations with any other construct. The bolded values in Table 3 highlight this relationship, reinforcing that each construct captures unique variance. This evidence of discriminant validity, in conjunction with the strong convergent validity results, validates the robustness of the measurement model and strengthens confidence in its application for further analysis.

Table 3: Assessment of discriminant validity using the Fornell-Larcker Criterion.

	Environmental Drivers (ED)	Operational Drivers (OD)	Pipe-Related Drivers (PRD)
ED	0.712		
OD	0.681	0.747	
PRD	0.612	0.677	0.770

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3.3 Measurement (Second-Order Construct)

As illustrated in Figure 2, the bootstrapping analysis reveals the path coefficients, highlighting the relative influence of key drivers on sewer corrosion. The results demonstrate a high convergence between the β -values, indicating strong consistency in the relationships among the constructs. These findings underscore the substantial roles of environmental drivers, operational drivers, and pipe-related drivers in contributing to sewer corrosion. Furthermore, all constructs achieve p-values of 0.000, satisfying the statistical significance threshold of $p \leq 0.05$. This confirms the robustness of the model and the strong influence of these factors, reinforcing their critical impact on sewer corrosion.

4. DISCUSSIONS

From the statistical analysis and from the measurement model, it was observed that environmental drivers (ED) have the highest impact on sewer corrosion, with a β -value of 0.369, indicating a strong variance allowance. Among these factors, sulfuric acid (ED3) ranks as the most critical, as it directly attacks concrete sewer walls, leading to significant deterioration (Mahmoodian & Alani, 2017). This is followed by H₂S gas (ED2), the primary precursor of sulfuric acid (Sun et al., 2019), which is oxidized by sulfur-oxidizing bacteria (SOB) (ED7), ranking third. This aligns with previous research confirming SOB's role in sewer corrosion (Jensen et al., 2011). Additional environmental contributors include sewer air temperature (ED1), relative humidity (ED4), and drying and wetting cycles (ED6), which result from the partially filled nature of sewer systems. These conditions, including the rise in temperature, the increase in relative humidity, and the repetition of dry and wet cycles, create an optimal environment for SOB growth, reinforcing earlier research findings (Anwar et al., 2022). Operational drivers (OD) follow environmental drivers (ED) closely, with only a slight difference in their β -values (0.369 for ED and 0.362 for OD), underscoring their strong influence on sewer corrosion. Among the operational factors, hydrogen sulfide (H₂S) (OD5) is the most influential, consistent with its widely recognized role as the primary trigger of corrosion onset (Anwar et al., 2022). It is followed by sulfate-reducing bacteria (SRB) (OD4), which accelerate H₂S formation by converting sulfates (OD1) through biochemical reactions (Silamat et al., 2024). Sulfates (OD1) occupy the third position in terms of corrosion impact, after H₂S and SRB, followed by temperature (OD2), BOD (OD6), pH (OD3), and dissolved oxygen (OD7) in wastewater. These factors collectively contribute to creating an anaerobic environment conducive to SRB activity, further validating findings from previous experimental and field studies (Pramanik et al., 2024). Pipe-related drivers (PRD) also exert a significant influence, with a β -value of 0.306, highlighting their role in sewer corrosion. Pipe age (PRD3) is identified as the most critical factor, as aging pipes lose structural integrity due to prolonged exposure to various environmental and operational stressors, making them more susceptible to corrosion (Hong et al., 2024). Following this, pipe length (PRD1) and diameter (PRD2) play important roles, as increased pipe length exposes a larger surface area to corrosion, while larger diameters lead to greater H₂S accumulation, exacerbating corrosion severity (Matias et al., 2017). Additionally, the properties of concrete pipes significantly impact corrosion resistance, with geopolymer concrete (PRD9) ranking as the most effective in mitigating corrosion, followed by concrete alkalinity (PRD6), porosity (PRD7), and cement type (PRD8)—all of which are supported by previous studies (Pramanik et al., 2024).

5. CONCLUSIONS

Sewer systems are continuously affected by corrosion, posing significant challenges to infrastructure durability. Despite extensive research on sewer corrosion, gaps remain in identifying the most influential drivers and their roles in initiating or accelerating deterioration. To address this issue, this study analyzed corrosion-causing factors through a comprehensive literature review, expert surveys, and PLS-SEM modeling. The results indicate that environmental factors have the greatest impact on sewer corrosion, followed closely by operational and pipe-related factors, with only minor differences in their influence, highlighting their collective significance. These findings provide valuable contributions to research, infrastructure management, and environmental protection. Academically, the study enhances existing models by confirming the critical roles of sulfuric acid (ED3), hydrogen sulfide (OD5), and pipe age (PRD3) in corrosion processes. Practically, municipalities and wastewater management agencies can prioritize

maintenance and implement preventive strategies to reduce unexpected failures. Engineers and construction firms can apply these insights in material selection, favoring geopolymers for improved durability. Policymakers can develop stricter wastewater treatment guidelines to limit corrosive substances, while mitigating sewer corrosion minimizes public health risks and environmental contamination, contributing to urban sustainability. However, this study has limitations. It focused on concrete sewers in China and Hong Kong, which may limit the generalizability of findings to other regions or materials. Factors like freezing and thawing of sewage, relevant in colder climates, were not considered due to their limited applicability in the study area. Additionally, while the sample size of 125 responses suffices for PLS-SEM analysis, it may not fully represent the diversity of global sewer networks, particularly in areas with unique environmental or operational conditions. Despite these constraints, the study provides actionable insights for understanding and mitigating sewer corrosion, offering a foundation for future research and practical applications. Overall, these findings provide essential guidance for researchers, engineers, policymakers, and utility agencies, helping to extend the lifespan of sewer systems and enhance wastewater infrastructure resilience.

ACKNOWLEDGMENTS

This work was supported by the Research Grants Council of the University Grants Committee [RGC-15209022] and the General Research Fund (GRF) [GRF-15202524] in Hong Kong.

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