

Understanding Key Factors Influencing Hydrogen Sulfide Emissions in Sewer Systems

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ABSTRACT: Hydrogen sulfide (H₂S) emissions are a major contributor to sewer corrosion, posing risks to infrastructure durability, public health, and the environment. A comprehensive understanding of the factors influencing H₂S formation and emissions remains incomplete despite extensive research. This study aims to analyze the impact of hydrogen sulfide factors (HSF) and evaluate their role in hydrogen sulfide impacts (HSI). The research follows a four-stage methodology. First, an extensive literature review and expert interviews were conducted to identify and categorize HSF. Second, a pilot survey was developed to refine the questionnaire, followed by the third stage, where a structured questionnaire was distributed to industry professionals. Finally, Structural Equation Modeling (SEM) was applied to analyze relationships among the identified factors. The results confirm a strong model, demonstrating the significant influence of HSF on HSI, with an R² value of 76.3%, highlighting the robustness of the proposed framework. This research provides critical insights for decision-makers, particularly infrastructure construction engineers, by prioritizing key factors that drive H₂S emissions and implementing effective mitigation strategies. Additionally, it aids environmental engineers and policymakers in developing preventive measures to minimize the environmental and health impacts of H₂S emissions. This study enhances the understanding of hydrogen sulfide emissions dynamics by offering a systematic and data-driven approach. It supports more informed decision-making for designing, operating, and maintaining resilient sewer networks.

Keywords: Infrastructure resilience - Environmental hazards - Hydrogen sulfide emissions – H₂S impacts -Structural Equation Modeling (SEM)

1. INTRODUCTION

Sewerage systems worldwide are plagued by corrosion and foul odors, often triggering complaints from nearby residents. In addition to being unpleasant, the gases released within these systems are toxic, with hydrogen sulfide (H₂S) serving as the primary agent responsible for odor, corrosion, and toxicity as it escapes from sewage into the headspace of sewer pipes. These issues result in significant economic burdens, with annual damages reaching \$14 billion in the U.S. and high costs reported globally. (Rathnayake et al., 2021). Hydrogen sulfide in sewers is primarily formed through the biological reduction of sulfate (SO₄²⁻) by sulfate-reducing bacteria (SRB) under anaerobic conditions in wastewater (Rathnayake et al., 2021). Several hydrogen sulfide factors (HSF) influence its formation and accumulation in sewer systems. (1) Operational factors (OF) are critical, including sulfate concentration, wastewater

temperature, pH levels, sulfate-reducing bacteria (SRB) activity, flow velocity, and retention time. High sulfate concentrations provide the necessary substrate for SRB, leading to increased H₂S production (Silamat et al., 2024). Elevated temperatures enhance SRB activity, accelerating sulfate reduction and increasing H₂S formation (Yongsiri et al., 2004). Similarly, low pH levels create favorable conditions for SRB, further promoting H₂S generation (Sharma et al., 2013). The activity of SRB, a key driver of H₂S formation, is directly influenced by environmental conditions, with optimal growth occurring under anaerobic and nutrient-rich conditions (Lors et al., 2018). Increased flow velocity induces turbulence, enhancing sulfate reduction in sediments and stimulating biofilm formation while reducing dissolved H₂S, leading to greater gaseous emissions (Zuo et al., 2021). Prolonged retention time promotes anaerobic conditions, fostering microbial growth and increasing H₂S concentration and emissions (Matias et al., 2017). (2) Pipe-related factors (PRF), such as pipe length and diameter, influence H₂S dynamics. Longer pipes promote the development of anaerobic conditions, enhancing SRB activity and leading to higher H₂S concentrations (Liang et al., 2019). Additionally, larger pipe diameters provide a greater surface area for H₂S accumulation, increasing the potential for its release into the sewer atmosphere (Luimes et al., 2022). (3) Environmental factors (EF), including air temperature, ventilation, and climate change, influence H₂S emissions. Higher air temperatures accelerate H₂S transfer to the gas phase (Jiang et al., 2014), while poor ventilation leads to its accumulation in sewer airspace (Guo et al., 2018). Climate change also raises sewer air temperatures, increasing H₂S concentrations (Zuo et al., 2019). Hydrogen sulfide in sewer systems has wide-ranging impacts, collectively called hydrogen sulfide impacts (HSI). One of the most noticeable effects is the emission of foul odors in surrounding areas, leading to discomfort and complaints from nearby residents (Zhang et al., 2008). H₂S also poses serious health risks for workers, as it is a toxic gas that can cause respiratory issues and, at high concentrations, even fatalities (Park et al., 2014). Structurally, H₂S leads to the formation of corrosive layers on sewer infrastructure, contributing to the accelerated deterioration of concrete and reducing the lifespan of sewer systems. Managing H₂S is costly, with high expenses for chemical treatments like nitrate or iron salt dosing to mitigate its effects. Additionally, H₂S promotes biofilm and sediment buildup, which restricts flow, increases blockages, and further exacerbates maintenance challenges within sewer pipes (Zhang et al., 2008). Despite extensive research on infrastructure systems, sewers remain one of the most vulnerable components, with H₂S emissions posing a significant threat. While numerous studies have investigated the factors affecting hydrogen sulfide through laboratory experiments, they often focus on a limited set of variables, failing to comprehensively understand the full range of contributing factors (Yongsiri et al., 2004). Moreover, sewer environments' complex and dynamic nature makes laboratory simulations challenging, leading to gaps in accurately replicating real-world conditions. Additionally, existing research lacks an integrated assessment of the impacts of hydrogen sulfide on sewer structural integrity, public health, and the surrounding environment. This study seeks to bridge these gaps by employing a statistical approach to analyze HSF and HSI, offering a more holistic perspective on H₂S generation and its consequences. The findings are expected to support construction and infrastructure engineers, as well as environmental professionals, in making informed decisions regarding sewer design, implementation, operation, and maintenance. By identifying the most influential factors contributing to H₂S emissions and the most affected indicators of sewer deterioration, this research aims to enhance sewer networks' longevity, safety, and sustainability, ultimately contributing to improved infrastructure management and environmental protection.

2. RESEARCH METHODS

This study adopts a four-step methodology, as illustrated in Figure 1. The steps include: (1) a comprehensive literature review and conducting interviews to identify key hydrogen sulfide factors (HSF) and their impacts (HSI); (2) a pilot survey to evaluate the clarity and relevance of the main questionnaire; (3) the design of a questionnaire to assess the significance of HSF in influencing HSI; and (4) the application of PLS-SEM to analyze the relationships between HSF and HSI in sewer systems.

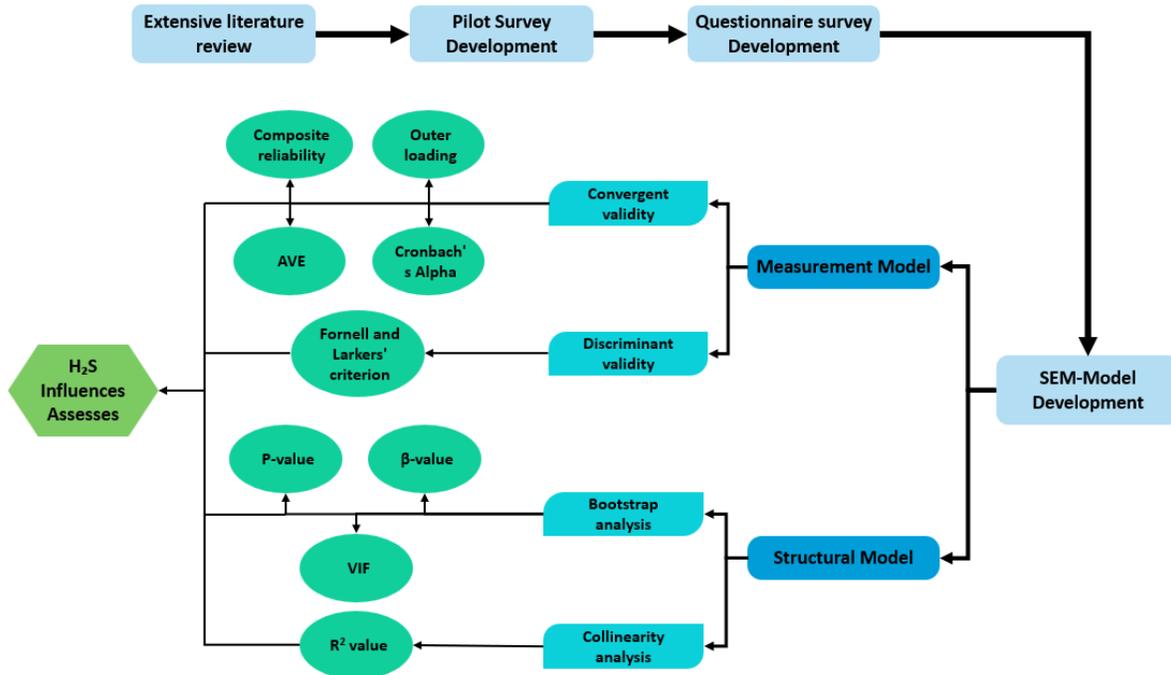


Figure 1: Research flowchart

2.1 Identification and Categorization of HSF and HSI

This study systematically identified and evaluated hydrogen sulfide factors (HSF) and hydrogen sulfide impacts (HSI) through an extensive literature review and expert consultations (Ibrahim et al., 2024a, 2024b). Relevant studies were gathered from academic databases such as Scopus and Web of Science (Elrifaae et al., 2024; Ibrahim et al., 2025). Following this, interviews were conducted with four experts in the fields of sewer systems and environmental engineering to refine the identified factors and establish appropriate categorization, as presented in Table 1. The interview methodology was adopted based on the approach outlined in (Naji et al., 2024).

Table 1: List of HSF and HSI with their relevant coding system.

Category	Type	Indicator	Code	References
OF	IDV1	• Sulfate (SO ₄ ²⁻) in wastewater	OF1	(Silamat et al., 2024)
		• Wastewater Temperature	OF2	(Yongsiri et al., 2004)
		• pH of wastewater	OF3	(Sharma et al., 2013)
		• SRB in wastewater	OF4	(Lors et al., 2018)
		• Turbulence (Flow Velocity)	OF5	(Zuo et al., 2021)
		• Retention Time (RT)	OF6	(Matias et al., 2017)
PRF	IDV2	• Length of Pipe	PRF1	(Liang et al., 2019)
		• Diameter of Pipe	PRF2	(Luimes et al., 2022)
EF	IDV3	• Temperature of the Air Space in the Sewer	EF1	(Jiang et al., 2014)
		• Ventilation Condition	EF2	(Guo et al., 2018)
		• Climatic Conditions (e.g., Global Warming)	EF3	(Zuo et al., 2019)
HSI	DV	• Foul Odors in Surrounding Areas	HSI1	(Zhang et al., 2008)
		• Health Risks for Workers	HSI2	(Park et al., 2014)
		• Formation of Corrosive Layers	HSI3	(Zhang et al., 2008)
		• Accelerated Sewer Concrete Deterioration	HSI4	(Pramanik et al., 2024)
		• High Cost of Chemical Treatments	HSI5	(Zhang et al., 2008)
		• Biofilm and Sediment Buildup	HSI6	(Park et al., 2014)

2.2 Pilot Survey Development

A pilot study assessed the questionnaire's clarity, relevance, and completeness (Tabatabaee et al., 2022). According to previous studies (Ali et al., 2023a; Daoud et al., 2023), pilot studies are considered valid with a minimum of 10 participants; therefore, 12 experts were involved, including nine industry professionals and three academics with over 10 years of experience. Their feedback focused on refining the wording of questions, identifying ambiguities, and validating the categorization of HSF and HSI. It is important to note that this pilot group was entirely separate from the main study participants used for statistical analysis. The pilot results demonstrated a Cronbach's alpha coefficient of 0.93, indicating excellent internal consistency and reliability of the questionnaire.

2.3 Questionnaire Survey Development

The questionnaire was divided into four sections. The first section collected general information about respondents. Section 2 focused on factors affecting the formation, emission, and build-up of H₂S in sewer environments. Section 3 assessed the impacts of H₂S on sewer systems, public health, and the environment. The final section included an open-ended question, allowing respondents to suggest additional factors or considerations relevant to the study. Two 5-point Likert scales were used to evaluate responses. The first scale measured HSF's 'level of efficacy,' with five indicating 'very effective' and one indicating 'not effective at all.' The second scale assessed HSF's 'degree of impact' on HSI, where 5 represented 'extremely high influence' and 1 represented 'very low influence'. All questionnaire items were designed to capture the personal opinions of experts, based on their professional experience, rather than quantitative measurements of the factors, as this approach allows for a broader assessment of H₂S formation causes across diverse real-world projects. This approach aligns with prior studies (Ismail et al., 2023). The questionnaire was distributed to sanitation professionals in China and Hong Kong through various channels. Respondents were prequalified based on two criteria: (1) possession of at least a bachelor's degree or equivalent in civil engineering, environmental science, or a related field, and (2) a minimum of five years of relevant experience in sanitation, sewer systems, or environmental management as practitioners or researchers. The sample size for research is determined by the objectives of the analysis (Ali et al., 2023a). For SEM analysis, a minimum of 100 cases is recommended (do Valle and Assaker, 2016). In this study, 130 valid responses were collected from sanitation professionals, meeting the requirement for SEM. The demographic profile of respondents is presented in Table 2.

Table 2: Demographic Information of Respondents.

Respondents' Profile		Frequency	Percentage%
Experience	5-10 years	39	30%
	11-15 years	74	57%
	16 years or more	17	13%
Education	Bachelor's degree	87	67%
	Diploma	13	10%
	Master's degree	19	15%
	Doctorate or other advanced degree	11	8%
Job role	Environmental Engineer	37	28%
	Wastewater Treatment Specialist	23	18%
	Sewer Maintenance Technician	19	15%
	Infrastructure Consultant	11	8%
	Researcher/Scientist	31	24%
	Project Manager	9	7%

2.4 SEM-Model Development

Structural Equation Modeling (SEM) aims to validate causal relationships between constructs represented by predefined variables, examining direct and indirect effects (Ali et al., 2023a). SEM involves a two-step process: (1) validating the measurement model using Confirmatory Factor Analysis (CFA) and (2) constructing the structural model to test hypotheses via path analysis (Xiong et al., 2015). SEM can be

conducted using covariance-based (CB-SEM) or component-based (PLS-SEM) approaches. PLS-SEM was selected for this study because it offers greater predictive accuracy, effectively handles multiple components, and provides stronger explanatory power for variance, making it suitable for analyzing complex relationships in H₂S emissions (Hair et al., 2019). The study uses PLS-SEM to assess the relationships between HSF and HIS.

2.4.1 Measurement Model

The PLS-SEM measurement model evaluates this study's constructs through convergent validity and discriminant validity tests (THAM et al., 2019). Convergent validity is assessed using four methods: (1) Outer Loadings represent the correlation between indicators and their constructs in reflective models. Loadings ≥ 0.7 are ideal, while values above 0.5 are acceptable (Ali et al., 2023b). (2) Composite Reliability (ρ_c): a more accurate measure than Cronbach's Alpha, as it accounts for factor loadings instead of weighing indicators equally (Cho et al., 2023). Values ≥ 0.7 indicate acceptance, and ≥ 0.8 indicate good reliability (Hock et al., 2010). The formula for Composite Reliability is given in "Eq. 1" (G.D. Garson, 2016).

$$[1] \rho_c = \frac{(\sum \lambda_i)^2}{(\sum \lambda_i)^2 + \sum \text{var}(\varepsilon_i)}$$

In this equation, λ_i represents the component loading of each indicator, while $\text{var}(\varepsilon_i)$ denotes the variance of the measurement error associated with each indicator. (3) Cronbach's Alpha (α) measures the internal consistency of indicators related to a construct. Despite its limitations, it is widely used and considered acceptable when exceeding 0.6 (Hock et al., 2010). (4) Average Variance Extracted (AVE) is used to assess convergent validity, determining how much variance in the indicators is captured by the latent construct relative to measurement error (Hair et al., 2013). To establish convergent validity, the AVE should exceed 0.5, indicating that the construct explains more than half of the variance in its indicators (Memon and Rahman, 2014). The formula for AVE is presented in "Eq. 2":

$$[2] \text{AVE} = \frac{\sum \lambda_i^2}{\sum \lambda_i^2 + \sum \text{var}(\varepsilon_i)}$$

In this study, SmartPLS software automatically calculated ρ_c , Cronbach's Alpha, and AVE. The software streamlines complex statistical computations, minimizes errors, and generates visual outputs for easier interpretation of results, thus enhancing the efficiency and accuracy of the research process.

In measurement models, discriminant validity is assessed using Fornell and Larcker's Criterion, which compares the square root of a construct's AVE with its correlations to other constructs. The square root of AVE must be greater than the construct's correlation with any other construct, indicating that the construct shares more variance with its indicators than with others (Memon et al., 2017).

2.4.2 Structural Model

The structural model in PLS-SEM is evaluated using bootstrap analysis and collinearity analysis. The bootstrap method is a resampling technique that assesses the significance of relationships between variables, providing accurate estimates of standard errors and confidence intervals. The bootstrap analysis includes three key components: the β -value, the p-value, and the Variance Inflation Factor (VIF) (Hair et al., 2019). (1) The β -value represents the strength of the relationship between constructs, indicating how much an exogenous latent variable influences an endogenous one. A β -value greater than 0.09 ($\beta > 0.09$) is considered acceptable, with higher values signifying more potent effects (Ali et al., 2023a). (2) The p-value measures the probability that observed relationships occurred by chance, determining the statistical significance of the model's paths. Path coefficients are considered significant when $p \leq 0.05$ (Hair et al., 2013). (3) The VIF assesses collinearity among constructs, ensuring that multicollinearity does not distort the model's estimates. A VIF score should not exceed 5 ($VIF \leq 5$) to confirm that collinearity is within acceptable limits (F. Hair Jr et al., 2014).

Collinearity analysis further evaluates the model through the R² value, which measures explanatory power. The R² value indicates the proportion of variance in the dependent variable explained by the independent

variables. An R^2 of 0.02 or higher is considered weak, 0.13 or higher is moderate, and 0.26 or above is substantial, reflecting the stronger predictive ability of the model (Ringle et al., 2014).

3. RESULTS AND DISCUSSIONS

This section analyzes data using statistical methods to evaluate measurement and structural models. Results, presented in tables and figures, will be interpreted to address research questions and hypotheses, providing valuable insights and contributing to the field. It highlights the study's key findings and their significance and discusses the results.

3.1 Convergent validity

3.1.1 Outer Loading

Figure 2 shows that indicators OF1, OF2, OF3, PRF1, PRF2, EF1, EF3, HSI1, and HSI4 have outer loadings above 0.7, indicating high reliability. Meanwhile, OF4, OF5, OF6, EF2, HSI2, HSI3, HSI5, and HSI6 have outer loadings above 0.6, which are still acceptable.

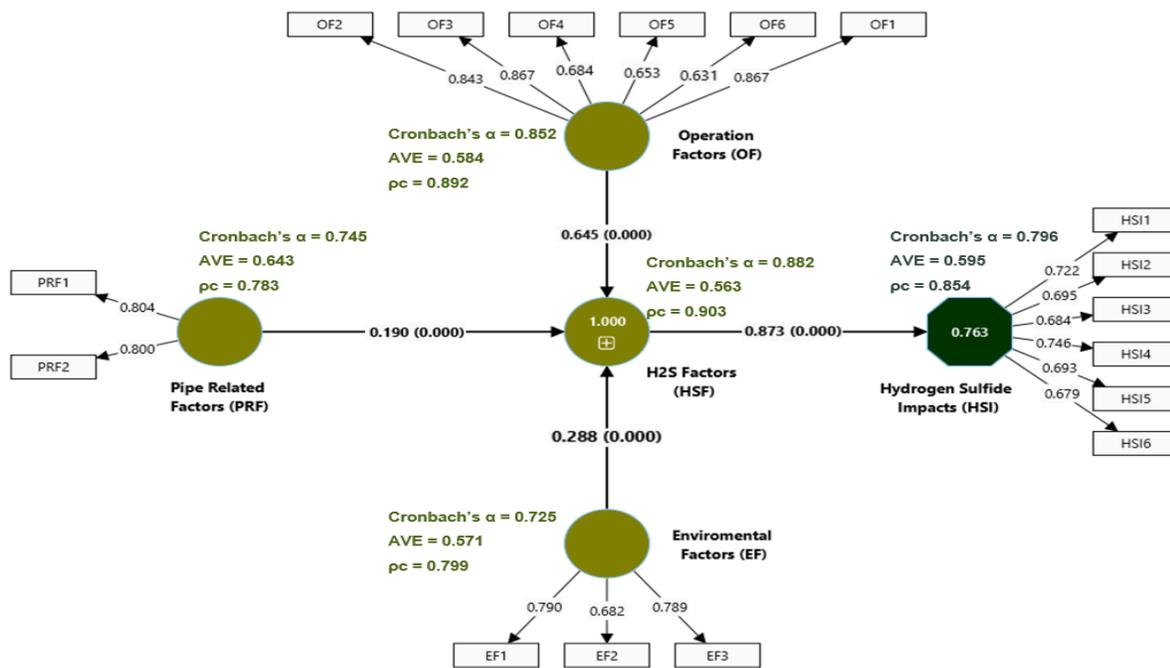


Figure 2: SEM-Model Results

3.1.2 Composite reliability (ρ_c)

All constructs meet the required Composite Reliability (ρ_c) threshold ($\rho_c > 0.7$), as shown in Figure 2, confirming their acceptability. Among these, the HSI construct achieved a Composite Reliability score above 0.8, indicating good reliability.

3.1.3 Cronbach's alpha (α)

As shown in Figure 2, all constructs meet the required Cronbach's Alpha (α) threshold ($\alpha > 0.6$), confirming their acceptability.

3.1.4 Average Variance Extracted (AVE)

The results indicate that all constructs have achieved the required thresholds for Average Variance Extracted (AVE) ($AVE > 0.5$), as illustrated in Figure 2, confirming their acceptability and strong performance. This demonstrates that the analytical model is convergent and consistent, ensuring the reliability and validity of the constructs' variables. Furthermore, the relationships among the constructs have been rigorously examined, providing evidence to support the theoretical relationships hypothesized in the study.

3.2 Discriminant validity (Fornell and Larcker Criterion)

Table 3 Presents the results of the Fornell and Larcker criterion. The bolded values indicate that the relationship between each construct and itself yields the highest value in its respective column.

Table 3: Discriminant validity - Fornell-Larcker criterion.

	EF	HSI	OF	PRF
EF	0.755			
HSI	0.715	0.771		
OF	0.686	0.703	0.764	
PFF	0.591	0.682	0.586	0.802

3.3 Bootstrapping Analysis

PLS-SEM was employed to evaluate and analyze the study's hypotheses regarding the effect of factors affecting hydrogen sulfide (HSF) and its impact on HSI. The bootstrapping method was used to assess the significance of the model's hypotheses, with results illustrated in Figure 2, including β and P-values for each relationship. For instance, the relationship between HSF and HSI was highly significant ($\beta = 0.873$, $P = 0.000$). Additionally, all Variance Inflation Factor (VIF) values were below the threshold of 5, confirming the absence of multicollinearity and their acceptability. The specific VIF values were as follows: $OF \rightarrow HSF = 2.089$, $PRF \rightarrow HSF = 1.697$, $EF \rightarrow HSF = 2.106$, and $HSF \rightarrow HSI = 1.000$.

3.4 Collinearity analysis - Explanatory power (R2 value)

The explanatory power of the model was determined using the Smart-PLS algorithm method, as presented in Table 4. The adjusted R^2 value for the dependent variable, HSI, is 0.763, indicating that 76.3% of the variance in HSI is explained by the three independent variables (HSF). This demonstrates the substantial influence of HSF on HSI. While an R^2 value greater than 0.26 is generally considered substantial, achieving 76.3% highlights the severe impact of hydrogen sulfide on environmental safety, sewer infrastructure, and public health. This underscores the significance of the model in understanding and addressing these critical issues.

Table 4: Results of explanatory power (R2 value)

Endogenous Latent Variable	R^2	Adj R^2	Explained size
HSI	0.763	0.761	Substantial

PLS-SEM was used to conduct a correlation analysis between HSF and HSI. The results indicate a significant effect of HSF on HSI, with a β -value of 0.873, underscoring the critical impact of hydrogen sulfide (H_2S) emissions on sewer infrastructure, workers' health, and environmental pollution. Among the factors influencing H_2S formation and sewer emissions, operational factors (OF) had the strongest influence on hydrogen sulfide (H_2S) emissions, with a β -value of 0.645. The sulfate concentration (OF1) and pH (OF3) exhibited the highest outer loading of 0.867. The wastewater temperature (OF2) followed, with an outer loading of 0.843. These findings align with previous studies (Sharma et al., 2013; Silamat et al., 2024; Yongsiri et al., 2004). Environmental factors (EF) ranked second in influence, with a β -value of 0.288. The most significant impact was observed for sewer air temperature (EF1), which had an outer loading of 0.790, followed by climate change, including global warming (EF3), with an outer loading of 0.789, as it contributes

to increasing sewer air temperature, thereby accelerating the transformation of H₂S from liquid to gas (Jiang et al., 2014). The effect of ventilation conditions (EF2) was lower, with an outer loading of 0.682, which supports previous research indicating that ventilation helps reduce H₂S concentrations, but only to a limited extent (Guo et al., 2018). Pipe-related factors (PRF) had the least impact, with a β -value of 0.19. The pipe length (PRF1) had an outer loading of 0.804, slightly higher than the pipe diameter (PRF2), which had an outer loading of 0.800. Prior studies suggest that pipe length affects the extent of the H₂S emission area, while pipe diameter influences the intensity of H₂S concentration (Matias et al., 2017). Regarding HSI, outer loading results revealed that the most significant impact of H₂S was on the acceleration of concrete sewer deterioration (HSI4), with a loading value of 0.746, consistent with previous findings (Pramanik et al., 2024). The second most significant impact was H₂S-related odor emissions (HSI1), with a loading value of 0.722, underscoring the necessity of controlling H₂S emissions to preserve air quality. The health risks for sewer maintenance workers (HSI2) ranked third, with a loading value of 0.695. Notably, H₂S exposure has led to numerous accidents, injuries, and fatalities among workers (Nielsen et al., 2008), making it imperative for governments to implement measures that mitigate H₂S formation and emissions to protect public health. These findings have practical implications for policymakers, engineers, and infrastructure managers. Since operational factors had the strongest influence on H₂S emissions, mitigation strategies should focus on monitoring sulfate levels, maintaining stable pH, and regulating wastewater temperature. Policymakers may consider setting standards for key wastewater parameters, while engineers can apply chemical dosing (e.g., nitrate or iron salts) methods and real-time H₂S detection to control emissions. Infrastructure managers should prioritize corrosion-resistant materials and routine maintenance, especially in high-risk areas. Improving ventilation and adapting to rising temperatures can also help reduce emissions and protect worker safety.

4. CONCLUSIONS

The formation and emission of hydrogen sulfide (H₂S) from sewers pose significant risks to public health, the environment, and the structural integrity of sewer systems. While previous studies have primarily examined individual factors influencing H₂S emissions, this study takes a comprehensive approach by evaluating multiple contributing factors (HSF) and assessing the impact of H₂S on sewer deterioration, air pollution, and worker safety (HSI) using Partial Least Squares Structural Equation Modeling (PLS-SEM). Data were collected from 130 sewer and environmental specialists in China and Hong Kong and analyzed through measurement and structural models in PLS-SEM. The findings reveal that operational factors (OF) are the most significant contributors to H₂S formation and emissions, exerting a substantial positive effect on sewer degradation, environmental pollution, and risks to sewer workers. In contrast, pipe-related factors (PRF) had a comparatively minor influence on H₂S emissions. The study's results confirm all three research hypotheses: operational factors (OF), pipeline-related factors (PRF), and environmental factors (EF), demonstrating that HSF has a significant impact on HIS. Nonetheless, this study has some limitations. The geographic focus on China and Hong Kong may affect the generalizability of the results to other regions. Additionally, while PLS-SEM is effective for modeling latent constructs, it may oversimplify the complex physical, chemical, and biochemical processes underlying H₂S formation. Future research should consider integrating PLS-SEM with mechanistic and reaction-based modeling approaches to capture these dynamics more accurately. Despite these limitations, this research provides valuable insights for decision-makers in environmental management and infrastructure project planning, helping them implement targeted strategies to mitigate H₂S emissions by prioritizing the most influential factors. Additionally, the findings serve as a practical guide for sewer operation and maintenance professionals, enabling them to adopt effective measures to reduce H₂S formation and its associated risks.

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