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Risk Causation and Safety Governance Pathways for Very Large-Scale Biogas (Biomethane) Projects Under Dual-Carbon Goals: A DEMATEL-ISM-Based Empirical Study

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Abstract

Very large-scale biogas (biomethane) projects are important infrastructure systems for integrating organic waste treatment, renewable energy substitution, and carbon mitigation under China's carbon peaking and carbon neutrality goals. However, their long process chains, concentrated hazardous media, and frequent confined-space operations create coupled safety risks that may undermine sustainable operation. To identify the dominant risk drivers and safety governance priorities, this study investigated five operating very large-scale biogas projects in Shanxi Province, China. On-site inspections, semi-structured interviews, and document reviews were used to identify ten safety-risk causative factors. The Decision-Making Trial and Evaluation Laboratory (DEMATEL) method was combined with Interpretive Structural Modeling (ISM) to quantify causal relationships and reveal the hierarchical transmission structure among the factors. The results show a structural imbalance between document-based compliance and operational implementation. Although basic safety documents were generally established, only 20% of the projects had scenario-specific emergency response plans for major accident scenarios; the compliance rate of explosion-proof electrical equipment, the configuration rate of fixed monitoring and alarm systems for combustible and toxic gases, and the effective operation rate of forced ventilation facilities were 40%, 60%, and 40%, respectively. Insufficient enterprise safety investment (M1) and unclear external regulatory responsibilities (M2) were the dominant root causes of system-level risk propagation, while inadequate control of high-risk operations (M9) and unsafe worker behavior (M10) were the final manifestations. A four-pillar governance pathway is proposed, including policy and standard improvement, technological support and equipment upgrading, personnel capacity enhancement, and sustainable funding mechanisms. The findings provide empirical evidence for risk-based supervision and indicate how operational safety governance can serve as an enabling condition for the long-term sustainability of the biomethane industry, rather than as a direct measurement of carbon-mitigation or energy-performance outcomes.

Keywords: very large-scale biogas project; biomethane; sustainability; operational safety; risk causation; DEMATEL-ISM; safety governance

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1. Introduction

Biogas and biomethane projects are increasingly regarded as practical components of the circular bioeconomy because they can convert livestock manure, crop straw, and other organic residues into renewable energy and organic fertilizer. Under China's carbon peaking and carbon neutrality goals, the industry is shifting from scattered and single-purpose utilization toward large-scale, engineered, and cluster-based development. Very large-scale biogas (biomethane) projects therefore connect agricultural waste valorization, rural energy substitution, pollution reduction, and carbon mitigation [1–4]. Previous studies have shown that waste-to-energy closed-loop supply chains can improve energy efficiency and environmental performance through circular energy supply and collaborative operation [2]. Life-cycle assessments have also demonstrated that biogas projects can generate environmental benefits compared with conventional fossil-energy systems [5]. At the regional scale, livestock manure and crop residues still have substantial potential for energy utilization, particularly in agricultural production clusters and ecologically fragile areas [6,7]. Recent studies have further emphasized that anaerobic digestion and biomethane systems should be assessed not only by energy output and greenhouse gas mitigation, but also by their circularity, environmental performance, operational reliability, and long-term governance capacity [8–12].

The sustainability of these projects depends not only on energy and environmental performance but also on their ability to operate safely over the long term. Compared with small and medium-sized facilities, very large-scale biogas projects have larger processing capacities, longer process chains, more concentrated hazardous media, more complex equipment, and more diverse operation and maintenance scenarios. Key units such as anaerobic digesters, gas holders, desulfurization systems, gas storage facilities, and generator rooms may lead to fire, explosion, poisoning, or asphyxiation if gas leakage, corrosion, overpressure, or failure of explosion-proof electrical systems occurs [13–15]. Confined-space work is a particularly critical high-risk operation during maintenance, sludge cleaning, tank inspection, and pipeline repair. If ventilation, gas testing, work permits, on-site supervision, and personal protective equipment are not implemented strictly, accidents may escalate rapidly and cause severe casualties [15,16]. A recent global analysis of biogas plant accidents reported that explosions, toxic gas releases, and asphyxiation were among the major accident types, and that component failure, maintenance errors, equipment failure, operational errors, and inadequate personal protection were important contributors to accident occurrence and severity [9]. National accident information has shown that confined-space operations are among the typical high-frequency and high-consequence accident scenarios in industrial and trade sectors [17].

Shanxi Province is a major energy province in China and has actively promoted the development of large and very large-scale biogas and biomethane projects. According to provincial industry records, by 2024, Shanxi Province had 29 large and very large-scale biogas projects, including biomethane projects. Nevertheless, systematic empirical studies on their safety status, risk structure, and governance pathways remain limited. From the perspective of risk-based regulatory governance, safety supervision should allocate regulatory attention and resources according to the likelihood and consequences of harm, which is consistent with the need for differentiated supervision of very large-scale biogas projects [18]. Existing research has mainly focused on the operation of small and medium-sized projects, consequence analysis of single facilities, general safety evaluation models, or industry development constraints [19–21]. Less attention has been paid to the coupling relationships among multi-actor, multi-process, and multi-level safety-risk factors in very large-scale projects. The Decision-Making Trial and Evaluation Laboratory (DEMATEL) method can identify the causal intensity and central role of factors in a complex system,

while Interpretive Structural Modeling (ISM) can reveal the hierarchical relationships among factors. Their integrated application has been reported in analyses of rural fires, urban gas networks, and agricultural machinery accidents [22–24], indicating its suitability for analyzing systemic safety risks in biogas projects.

Accordingly, this study selected five typical operating very large-scale biogas projects in Shanxi Province as empirical cases. The objectives were to: (1) identify key risk causative factors through field investigations, interviews, and document reviews; (2) analyze causal relationships and hierarchical risk transmission pathways using the DEMATEL-ISM model; (3) propose targeted safety governance pathways for the sustainable development of very large-scale biogas projects. The contribution of this study is threefold. First, it treats very large-scale biogas projects as a distinct research object and enriches empirical evidence on renewable-energy infrastructure safety. Second, it constructs a causative-factor system covering regulation, enterprise responsibility, safety investment, institutional implementation, facilities, personnel behavior, and high-risk operations. Third, it reveals a multi-level transmission structure from root causes to direct risk manifestations, thereby supporting differentiated supervision and precise governance. By linking operational safety with sustainability-oriented infrastructure governance, this study extends the discussion of biomethane projects from energy and environmental performance to the institutional, technological, human, and financial conditions required for long-term safe operation.

To further clarify the analytical focus, this study is organized around four research questions: RQ1—what are the main safety-status gaps in the investigated very large-scale biogas projects? RQ2—how do the identified safety-risk causative factors interact and transmit across governance, management, technical-barrier, and operational layers? RQ3—how are major risks distributed across key process stages, and what cost-sensitive control priorities can be inferred? RQ4—how can safety governance be strengthened as an enabling condition for sustainable biomethane infrastructure operation?

It should be noted that this study treats operational safety governance as an enabling condition for sustainable operation. It does not directly quantify greenhouse-gas mitigation, energy conversion performance, environmental impacts, or economic sustainability; therefore, statements regarding dual-carbon goals are interpreted in terms of risk prevention and continuity of biomethane infrastructure operation.

2. Materials and Methods

2.1. Case Projects and Data Sources

A multi-source case study design was adopted. The research objects were five operating very large-scale biogas (biomethane) projects in Shanxi Province. Their feedstocks mainly included livestock manure and crop straw, and their process chains covered feedstock reception and pretreatment, anaerobic digestion, gas desulfurization and dehydration, gas storage, power generation or biomethane upgrading, and digestate utilization. The sampled projects included both state-owned and private enterprises, which provided a basis for exploratory comparison of safety investment, institutional implementation, and risk control across ownership types. In this study, "very large-scale biogas projects" refers to centralized biogas or biomethane facilities with a total effective anaerobic digester volume of 5000 m^3 or above.

The five cases were selected using purposive sampling from the provincial set of large and very large-scale biogas and biomethane projects. Inclusion criteria were as follows: (i) the project was in operation during the investigation period; (ii) the total effective anaerobic digester volume was 5000 m^3 or above; (iii) the process chain covered at least anaerobic digestion, gas treatment, gas storage or utilization, and digestate management; (iv) on-site access to safety facilities, documents, and key personnel was available. Projects that were

under construction, permanently suspended, or unable to provide basic operational and safety-management information were excluded. Anonymized project-level characteristics are provided in Supplementary Table S1 to clarify case comparability and transferability.

Data were obtained from three complementary sources. First, on-site inspections were conducted for anaerobic digesters, gas holders, desulfurization units, generator rooms, confined-space work locations, and explosion-hazardous areas. Safety facilities, gas monitoring and alarm systems, ventilation facilities, emergency supplies, and warning signs were checked against observed risk locations. Second, semi-structured interviews were conducted with enterprise managers, safety officers, operation and maintenance staff, and frontline workers. The interviews focused on safety responsibility, training and assessment, work permits, hazard identification and rectification, and emergency drills. Third, document review was used to examine safety responsibility systems, operating procedures, confined-space work systems, hazard inspection records, training files, emergency plans, and drill records. This design enabled a joint assessment of institutional completeness and the consistency between written requirements and on-site implementation.

The interviews were conducted in a semi-structured format during the field investigation. Interviewees included project managers, safety officers, operation and maintenance staff, and frontline workers. Interview notes were anonymized immediately after the investigation, and no personally identifiable information was retained. A total of 15 interviewees participated in the semi-structured interviews, and the interview information was coded and summarized according to predefined themes, including safety responsibility, training, work permits, hazard remediation, emergency response, facilities, and high-risk operations. The extracted themes were then cross-checked with field observations and document-review evidence before being used for factor identification. The inspection checklist, assessment criteria, and case-level results underlying the reported percentages are provided in Supplementary Tables S2 and S3.

For process-stage analysis, the process chain was further disaggregated into feedstock reception and pretreatment, anaerobic digestion, gas cleaning and storage, energy utilization or biomethane upgrading, digestate management, and maintenance/confined-space operations. For each stage, typical risk points, safety barriers, and cost-sensitive control implications were summarized from field observations, document review, and interview evidence. Because detailed enterprise cost records were confidential and not directly comparable across projects, this study did not conduct monetary cost accounting. Instead, it used a qualitative cost-burden classification (low, medium, high, and long-term operational cost) to link safety gaps with feasible investment priorities.

2.2. Identification of Safety-Risk Causative Factors

Risk causative factors were extracted based on a literature review, field evidence, and expert consultation. The initial factors were grouped into five dimensions: enterprise management, regulatory systems, personnel competence, facilities and equipment, and high-risk operations. To ensure interpretability and operability, overlapping factors were merged according to repeatedly observed problems during the investigation. Ten key causative factors (M1–M10) were finally identified. These factors include root drivers, such as insufficient enterprise safety investment, unclear external regulatory responsibilities, and weak awareness of enterprise safety responsibility; intermediate management factors, such as lack of professional training systems and ineffective implementation of safety management systems; and direct risk manifestations, such as incomplete safety facilities, inadequate high-risk operation control, and unsafe worker behavior.

To improve traceability, the factor-development process was clarified as follows. An initial pool of risk items was compiled from literature evidence, field-observed deficiencies,

document-review findings, and interview notes. Items with similar meanings or the same governance implication were merged, while items without repeated evidence across data sources were retained only when experts judged them to be critical for accident prevention. The final ten factors were validated through expert discussion until no additional high-frequency or high-consequence factor was identified. Operational definitions, supporting field evidence, and evidence-to-factor mapping are reported in Supplementary Table S4.

2.3. DEMATEL Analysis

DEMATEL was used to characterize the direct and indirect influence relationships among the factors. Five experts with backgrounds in safety evaluation, industry regulation, and engineering technology were invited to form an evaluation panel. Based on field evidence and professional judgment, the experts conducted pairwise assessments of the direct influence among the ten factors using a 0–4 scale: 0 = no influence, 1 = weak influence, 2 = moderate influence, 3 = strong influence, and 4 = very strong influence. The averaged expert scores were used to construct the direct influence matrix A.

The expert panel consisted of five anonymized experts covering safety evaluation, industry regulation, academic research, engineering design, and enterprise operation. All experts had professional experience related to biogas engineering, safety assessment, process operation, or regulatory supervision, and none was directly responsible for the daily management of the sampled projects. Before scoring, disagreements on factor meanings were discussed to ensure a shared understanding of M1–M10, but individual pairwise scores were submitted independently. Inter-rater consistency was assessed using rank correlations and dispersion statistics, and leave-one-expert-out checks were performed to examine whether the main causal interpretation remained stable. The expert profiles and agreement results are provided in Supplementary Tables S5 and S6.

The normalized direct influence matrix D was calculated as follows:

$$D = \frac{A}{s} \tag{1}$$

where s is the maximum value among all row sums and column sums of matrix A. $s = \max(\max_{1\le i\le n}\sum_{j=1}^{n} a_{ij}, \max_{1\le j\le n}\sum_{i=1}^{n} a_{ij})$.

The total influence matrix T was then obtained as:

$$T = D\Big(I - D)^{-1} \tag{2}$$

The total influence matrix captures the accumulated effects of direct and indirect influences. The influencing degree D_i, influenced degree C_i, centrality M_i, and relation degree R_i were calculated as follows:

$$D_i = \sum_{j=1}^{n} t_{ij} \tag{3}$$

$$C_i = \sum_{j=1}^{n} t_{ji} \tag{4}$$

$$M_i = D_i + C_i \tag{5}$$

$$R_i = D_i - C_i \tag{6}$$

The influencing degree denotes the comprehensive influence of a factor on other factors, whereas the influenced degree denotes the extent to which it is affected by others. Centrality reflects the overall importance of a factor in the system, and the relation degree distinguishes cause factors from effect factors. If $R_i > 0$, the factor mainly acts as a cause factor; if $R_i < 0$, the factor mainly acts as an effect factor.

2.4. ISM Analysis

ISM was used to reveal the hierarchical structure among the causative factors. According to the total influence matrix T and a threshold λ determined through expert discussion, the adjacency matrix B was defined as:

$$b_{ij} = \begin{cases} 1, & \text{if} t_{ij} \geq \lambda \\ 0, & \text{if} t_{ij} < \lambda \end{cases} \quad (7)$$

The reachability matrix M was then obtained by Boolean operation of the adjacency matrix B and the identity matrix I:

$$M = (B + I)^k \quad (8)$$

where k is the power exponent. In Equation (7), b_{ij} denotes the element of the adjacency matrix B derived from the total influence matrix element t_{ij} and threshold λ. The reachability matrix was calculated using Boolean operations until $(B + I)^{k-1} \neq (B + I)^k = (B + I)^{k+1}$, where addition and multiplication are Boolean rather than arithmetic operations. Hierarchical division was then conducted using the reachability set $R(S_i)$, antecedent set $A(S_i)$, and common set $C(S_i)$:

$$R(S_i) = \{S_j \mid m_{ij} = 1\} \quad (9)$$

$$A(S_i) = \{S_j \mid m_{ji} = 1\} \quad (10)$$

$$C(S_i) = R(S_i) \cap A(S_i) \quad (11)$$

If $R(S_i) = C(S_i)$, the corresponding factor was assigned to the current level. After removing the factors at that level, the process was repeated until all factors were classified. The combined DEMATEL-ISM procedure therefore enabled both the identification of dominant drivers and the visualization of risk transmission layers.

2.5. Methodological Reliability and Robustness

To improve the reliability of the DEMATEL-ISM procedure, this study adopted a multi-source triangulation strategy. The identification of causative factors was not based solely on expert judgment, but was derived from the convergence of field inspections, semi-structured interviews, document reviews, literature evidence, and expert consultation. The expert-scoring process was conducted after the field investigation, allowing pairwise judgments to be based on observed safety problems rather than only on general experience. The expert panel covered regulatory supervision, engineering operation, and safety evaluation perspectives, which helped reduce single-perspective bias in the pairwise assessment.

The direct influence matrix was obtained by averaging the pairwise scores of five experts. The normalization factor was s = 25.8, and the total influence matrix was calculated as $T = D(I - D)^{-1}$. To examine the stability of the ISM interpretation, the threshold λ was set at 0.06 after expert discussion. A sensitivity check was conducted by varying λ within a reasonable range around the selected threshold. The results showed that the four-layer hierarchical structure remained unchanged, indicating that the main ISM interpretation was stable.

The selected threshold was further examined at λ = 0.055, 0.060, 0.070, and 0.074. Across these values, M1, M2, and M3 remained in the root-cause layer, whereas M9 and M10 remained in the direct manifestation layer. Leave-one-expert-out checks also retained the same dominant source drivers and terminal manifestations. The direct influence matrix, normalized matrix, total influence matrix, adjacency matrix, reachability matrix, and threshold sensitivity results are reported in Supplementary Tables S7–S12.

3. Results

To provide a clearer summary of the field findings, the key safety status indicators of the investigated projects are summarized in Table 1. Because the safety-status indicators are based on five projects, counts are reported together with percentages and should be interpreted as descriptive case proportions rather than population-level statistical rates.

Table 1. Summary of key safety status indicators for the investigated projects.

Assessment Dimension	Indicator	Result	Interpretation for Safety Governance
Institutional documentation	Establishment of basic safety responsibility systems and operating procedures	5/5 projects; 100%	Basic document-based compliance was generally achieved.
Emergency preparedness	Scenario-specific emergency response plans for major accident scenarios	1/5 projects; 20%	Emergency preparedness for biogas leakage, confined-space incidents, fire, and explosion remained insufficient.
Explosion-hazard electrical safety	Compliance rate of explosion-proof electrical equipment in explosion-hazardous areas	2/5 projects; 40%	The intrinsic safety barrier in hazardous areas was weak.
Gas monitoring and early warning	Configuration rate of fixed monitoring and alarm systems for combustible and toxic gases in key risk areas	3/5 projects; 60%	Early-warning capacity was not fully established.
Ventilation control	Effective operation rate of forced ventilation facilities	2/5 projects; 40%	Ventilation control for confined-space and gas-accumulation risks was inadequate.
Training, certification, and implementation records	Ownership-related differences in safety management	Observed	In the sampled projects, state-owned enterprises generally showed more standardized training, certification, documentation, and work-permit implementation than private enterprises.

3.1. General Characteristics

The investigated projects were all very large-scale biogas or biomethane projects. They were characterized by large processing capacities, relatively complete process chains, and a high concentration of facilities and equipment. Their feedstocks were mainly livestock manure and crop straw, and some projects also treated other agricultural organic wastes. The process systems generally included feedstock reception and pretreatment, anaerobic digestion, gas desulfurization and dehydration, gas storage, power generation or biomethane upgrading, and digestate utilization. These characteristics imply continuity of safety risk along the process chain and spatial concentration of hazards. Failure of any critical unit may propagate through gas leakage, pressure abnormality, equipment malfunction, or unsafe operation.

3.2. Safety Management Systems

All five projects had established basic safety responsibility systems and operating procedures, giving a 100% establishment rate for fundamental institutional documents. However, document completeness did not necessarily translate into management effectiveness. Only 20% of the projects had developed scenario-specific emergency response plans for key scenarios such as biogas leakage, confined-space poisoning or asphyxiation,

and fire or explosion. Some emergency plans were too general and did not adequately match the specific process flows, risk locations, personnel arrangements, and emergency resources of the projects.

Institutional implementation also varied across ownership types. State-owned enterprises generally had more standardized records for safety meetings, training, hazard identification and rectification, and work permits. In contrast, private enterprises showed problems such as discretionary implementation, incomplete records, and insufficient closed-loop rectification. This indicates a structural imbalance: institutional arrangements at the document level were relatively complete, while operational implementation remained insufficient. Such an imbalance may lead to a false sense of compliance and weaken the practical resilience of safety management systems.

These ownership-related patterns were treated as exploratory observations. Alternative explanations, including operating age, capacity, profitability, process configuration, and regulatory exposure, may also influence safety-management performance and should be examined in larger samples.

3.3. Safety Facilities and High-Risk Operation Control

Insufficient configuration of critical safety facilities was one of the most prominent common problems. Among the sampled projects, the compliance rate of explosion-proof electrical equipment in explosion-hazardous areas was 40%; the configuration rate of fixed monitoring and alarm systems for combustible and toxic gases in key risk areas was 60%; and the effective operation rate of forced ventilation facilities was 40%. Some projects had installed gas alarms, but their layout, calibration, maintenance, or integration with the central control system was inadequate, reducing their ability to support early warning and coordinated response.

The terms “compliance”, “configuration rate”, “effective operation”, and “scenario-specific emergency response plan” were assessed using predefined checklist criteria based on document verification and on-site confirmation. The criteria and case-level results are shown in Supplementary Tables S2 and S3.

High-risk operations, especially confined-space work, remained weakly controlled. Some project operators had insufficient risk identification for sludge cleaning, maintenance, tank inspection, and pipeline repair. Requirements for work permits, ventilation before entry, gas testing, on-site supervision, and emergency rescue preparation were not consistently implemented. Because methane, hydrogen sulfide, and carbon dioxide may accumulate in confined spaces in biogas projects, unauthorized or poorly prepared entry can easily lead to poisoning, asphyxiation, or secondary casualties caused by unprotected rescue attempts.

3.4. Training and Emergency Response Capability

Training and emergency response capacity also differed across the sampled projects. State-owned operators tended to show more standardized training records and certification mechanisms for special operations, whereas private operators showed more visible gaps in training frequency, content specificity, qualification management, and drill evaluation. Some frontline workers had insufficient knowledge of biogas leakage, hydrogen sulfide hazards, confined-space permits, and personal protective equipment.

In terms of emergency drills, some projects focused more on maintaining drill records than on testing practical emergency response capacity. Drill scenarios were relatively simple and did not fully cover high-consequence events such as gas leakage, fire and explosion, or confined-space poisoning and asphyxiation. Drill evaluation and corrective actions were also insufficient. Overall, the key shortcomings were insufficient safety investment,

incomplete critical safety barriers, inadequate professional training, and weak process control for high-risk operations.

Above all, Table 1 indicates that the investigated projects had generally achieved document-based compliance, but the transformation of written requirements into effective operational control remained insufficient. The low proportions of scenario-specific emergency response plans, compliant explosion-proof electrical equipment, and effective forced ventilation facilities suggest that the main weakness was not the absence of basic safety documents, but the inadequate configuration and implementation of key safety barriers. The ownership-related differences further imply that differentiated supervision and targeted support are needed for project operators with weaker safety investment and implementation capacity.

3.5. Causative-Factor System

Based on field investigation, interviews, and expert consultation, ten safety-risk causative factors were identified, as shown in Table 2. The system covers the main risk chain from external regulation, enterprise responsibility, and safety investment to institutional implementation, facilities and equipment, personnel behavior, and high-risk operation control. It therefore reflects the systemic characteristics of safety risks in very large-scale biogas projects.

Table 2. List of safety-risk causative factors.

Factor Code	Risk Causative Factor
M1	Insufficient enterprise safety investment
M2	Unclear external regulatory responsibilities
M3	Weak awareness of enterprise safety responsibility
M4	Lack of a professional training system
M5	Ineffective implementation of safety management systems
M6	Incomplete configuration of critical safety facilities
M7	Equipment aging and insufficient maintenance
M8	Ineffective emergency drills
M9	Inadequate control of high-risk operations, such as confined-space work
M10	Unsafe worker behavior

3.6. DEMATEL Results

The DEMATEL results show that factors with positive relation degrees act mainly as drivers, whereas factors with negative relation degrees are mainly outcomes of the system. As shown in Figure 1, M1, M2, and M3 were located in the cause-factor region, indicating that insufficient enterprise safety investment, unclear external regulatory responsibilities, and weak awareness of enterprise safety responsibility were source-level drivers of risk propagation. In contrast, M9 and M10 were located in the effect-factor region, suggesting that inadequate control of high-risk operations and unsafe worker behavior were terminal manifestations of systemic management failure. Centrality analysis indicated that M1, M2, M3, M5, and M9 had relatively high system relevance. Therefore, safety governance should address both source-level drivers and terminal operational risks, rather than focusing only on corrective measures after unsafe behavior occurs.

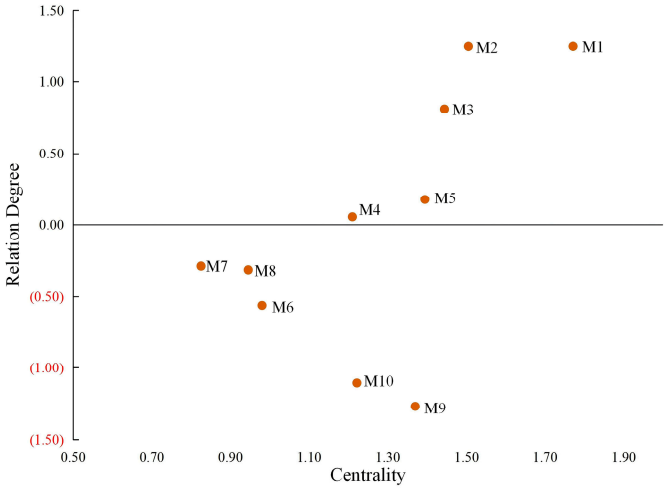


Figure 1. Centrality-relation degree diagram of the safety-risk causative factors.

3.7. ISM Hierarchical Structure

ISM divided the ten causative factors into four levels (Figure 2). L4, the root-cause layer, included M1 (insufficient enterprise safety investment), M2 (unclear external regulatory responsibilities), and M3 (weak awareness of enterprise safety responsibility). These factors determine whether an enterprise has sufficient internal and external motivation for continuous safety investment, proactive risk management, and strict institutional implementation. L3, the management support layer, included M4 (lack of a professional training system) and M5 (ineffective implementation of safety management systems), reflecting the ability to transform safety documents into on-site execution. L2, the system failure layer, included M6 (incomplete configuration of critical safety facilities), M7 (equipment aging and insufficient maintenance), and M8 (ineffective emergency drills). This layer represents the direct manifestation of inadequate management support in facilities, equipment, and emergency capability. L1, the direct manifestation layer, included M9 (inadequate control of high-risk operations such as confined-space work) and M10 (unsafe worker behavior), which are the risk states closest to accident occurrence. The ISM results indicate that the safety problems of very large-scale biogas projects are not isolated deficiencies but rather a hierarchical transmission process from root drivers through management support and safety barriers to direct operational risks.

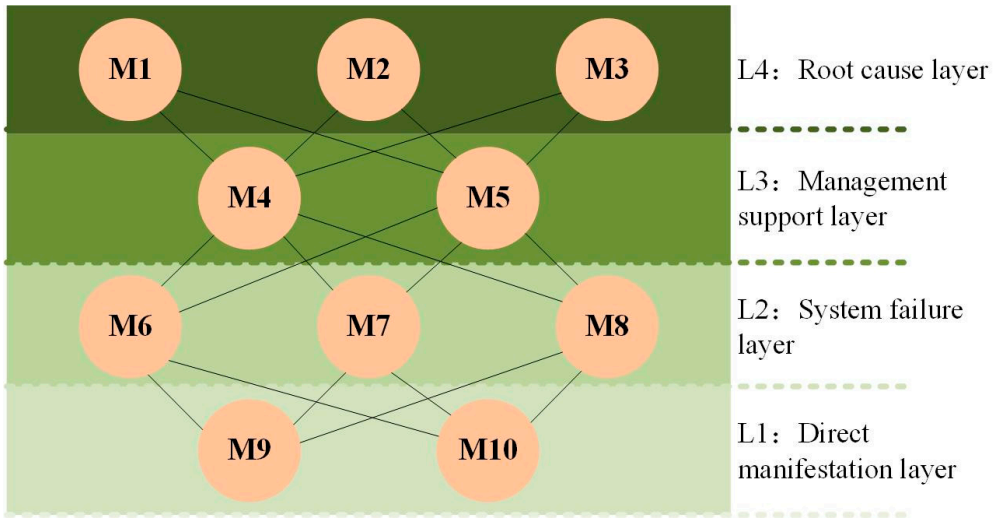


Figure 2. Interpretive structural model with directed inter-layer risk-transmission pathways of the safety-risk causative factors.

The directed arrows in Figure 2 represent the reduced inter-layer transmission relationships derived from the reachability structure. To avoid visual overcrowding, repeated within-layer feedback relationships are discussed in the text and reported in the supplementary matrices rather than being displayed as additional edges.

Figure 1 visualizes the centrality-relation degree distribution of the causative factors, whereas Table 3 provides the complete DEMATEL-ISM results, including influencing degree, influenced degree, centrality, relation degree, causal attribute, hierarchical layer, and governance implications. Table 3 confirms that M1 and M2 had the highest positive relation degrees, while M9 and M10 had the most negative relation degrees. The integrated DEMATEL-ISM results therefore support a clear transmission pathway from source-level drivers to management support deficiencies, system barrier failures, and direct operational risks.

Table 3. Integrated DEMATEL-ISM results of the safety-risk causative factors.

Factor Code	Risk Causative Factor	D_i	C_i	M_i	R_i	DEMATEL Attribute	ISM Layer	Governance Implication
M1	Insufficient enterprise safety investment	1.5093	0.2617	1.7710	1.2477	Source driver	L4: Root-cause layer	Establish sustainable safety investment and funding mechanisms.
M2	Unclear external regulatory responsibilities	1.3761	0.1288	1.5049	1.2472	Source driver	L4: Root-cause layer	Clarify regulatory boundaries and strengthen risk-based supervision.
M3	Weak awareness of enterprise safety responsibility	1.1285	0.3155	1.4440	0.8130	Source driver	L4: Root-cause layer	Strengthen enterprise responsibility and internal safety motivation.
M4	Lack of a professional training system	0.6322	0.5777	1.2099	0.0546	Cause factor	L3: Management support layer	Establish hierarchical and task-specific training systems.
M5	Ineffective implementation of safety management systems	0.7856	0.6087	1.3943	0.1770	Cause factor	L3: Management support layer	Reduce the gap between formal documents and on-site implementation.
M6	Incomplete configuration of critical safety facilities	0.3163	0.6288	0.9451	−0.3124	Effect factor	L2: System failure layer	Upgrade critical safety facilities and strengthen safety barriers.
M7	Equipment aging and insufficient maintenance	0.2693	0.5558	0.8251	−0.2865	Effect factor	L2: System failure layer	Implement life-cycle inspection, maintenance, and renewal.
M8	Ineffective emergency drills	0.2094	0.7709	0.9802	−0.5615	Effect factor	L2: System failure layer	Improve scenario-based drills and post-drill rectification.
M9	Inadequate control of high-risk operations such as confined-space work	0.0492	1.3206	1.3697	−1.2714	Key effect factor	L1: Direct manifestation layer	Strengthen work permits, ventilation, gas testing, supervision, and rescue preparation.

Table 3. *Cont.*

Factor Code	Risk Causative Factor	D_i	C_i	M_i	R_i	DEMATEL Attribute	ISM Layer	Governance Implication
M10	Unsafe worker behavior	0.0569	1.1645	1.2214	−1.1075	Key effect factor	L1: Direct manifestation layer	Strengthen operational compliance and behavior-based safety management.

Notes: D_i denotes the influencing degree; C_i denotes the influenced degree; M_i denotes centrality; Ri denotes the relation degree. A positive R_i indicates a cause factor, whereas a negative R_i indicates an effect factor.

3.8. Risk Transmission Mechanism

Based on the hierarchical structure and DEMATEL attributes, the risk transmission mechanism can be interpreted as a process of source-level governance failure, management support weakness, safety barrier degradation, and operational risk manifestation. At the source level, ambiguous regulatory boundaries weaken external constraints and enforcement consistency, reducing stable pressure on project operators to invest in safety, upgrade facilities, and remediate identified hazards. Weak awareness of enterprise safety responsibility further lowers the priority of safety management, leading to insufficient investment, incomplete training systems, and ineffective institutional implementation.

In the intermediate transmission stage, inadequate training and weak implementation of safety systems reduce workers' risk recognition and on-site compliance. This leads to incomplete critical safety facilities, delayed equipment maintenance, and low-quality emergency drills. Once these system barriers fail, key control measures for high-risk operations, including work permits, gas testing, ventilation, on-site supervision, and rescue preparation, cannot function effectively. The final manifestations are unsafe entry, non-standard operations, and unprotected rescue attempts. Therefore, safety improvement should not rely only on reactive correction at the operational end. Instead, root causes should be addressed through coordinated governance involving regulation, investment, technology, personnel, and institutional implementation.

3.9. Process-Stage Risk Distribution

The process-stage analysis indicates that safety risks were not evenly distributed along the project chain (Figure 3). Feedstock reception and pretreatment mainly involved mechanical injury, odor exposure, and uncontrolled mixing risks; anaerobic digestion and gas storage involved methane accumulation, hydrogen sulfide exposure, overpressure, corrosion, and explosion hazards; energy utilization and biomethane upgrading were associated with electrical ignition sources, pressure abnormality, and equipment failure; digestate management and sludge handling increased the probability of secondary exposure; and maintenance and confined-space operations represented the highest-consequence scenario because poisoning, asphyxiation, and unprotected rescue attempts may occur within a short time.

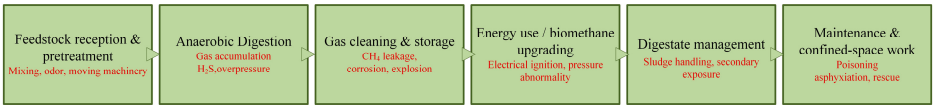


Figure 3. Process-stage risk flow chart for very large-scale biogas and biomethane projects.

Detailed plant-level strategy comparisons, process-stage risk distribution, and qualitative cost-burden classifications are provided in Supplementary Tables S13–S15.

4. Discussion

Based on the DEMATEL-ISM results, this study proposes a safety–sustainability governance framework for very large-scale biogas projects. The framework consists of four interrelated components: regulatory foundation, technological barriers, human competence, and financial sustainability. The regulatory foundation responds mainly to the root-cause factors of unclear regulatory responsibilities and weak enterprise responsibility awareness; technological barriers address system failures related to incomplete safety facilities and equipment aging; human competence targets training deficiencies and unsafe worker behavior; and financial sustainability provides the resource basis for continuous safety improvement. Compared with reactive correction after operational failures, this framework emphasizes source-oriented, life-cycle, and system-based governance.

These findings are consistent with established process-safety and barrier-management approaches, which emphasize layered safeguards, scenario-based hazard identification, and the integration of technical, organizational, and human factors [25–29]. Compared with HAZOP, bow-tie analysis, layers of protection analysis, and quantitative risk assessment, the DEMATEL-ISM approach used in this study does not replace scenario-specific engineering risk assessment. Instead, it provides a complementary governance-level tool for identifying upstream drivers and transmission layers that may weaken process-safety barriers in very large-scale biogas projects.

4.1. Improve Policy and Standard Systems

Because M2 and M3 are located in the root-cause layer, regulatory clarity and enterprise responsibility should be treated as institutional prerequisites for effective safety governance. A dedicated safety management system for very large-scale biogas and biomethane projects is therefore needed to address unclear project classification, regulatory responsibilities, and local technical requirements. Clearer responsibility boundaries among agricultural and rural affairs authorities, emergency management authorities, and fire and rescue authorities are necessary in relation to planning and construction, operational supervision, confined-space work, hazardous media management, and emergency response. Information sharing, joint inspection, and hazard reporting and referral mechanisms would further support coordinated risk-based supervision. This is consistent with the principle of risk-based regulatory governance, which emphasizes that regulatory systems should focus on high-risk facilities, high-consequence activities, and practical implementation gaps rather than only formal compliance [18].

In addition, local technical specifications or group standards are needed according to the processing scale, hazard characteristics, and operation and maintenance needs of very large-scale projects. Key requirements should cover explosion-proof electrical equipment, online combustible and toxic gas monitoring and alarms, confined-space work permits, regular equipment inspection, emergency plan preparation, and drill evaluation. Standardized requirements should integrate safety baselines into design, construction, operation, and maintenance, thereby providing a clear basis for regulatory enforcement and enterprise self-inspection [30,31].

4.2. Strengthen Technological Support and Equipment Upgrading

This pathway mainly addresses M6 and M7 in the system failure layer, where incomplete safety facilities and equipment aging weaken the technical barriers against accidents. Technological support and equipment upgrading are essential for reducing accident probability and controlling accident consequences. Fixed online monitoring and alarm devices for methane, hydrogen sulfide, and other gases should be installed in anaerobic digester areas, gas holders, desulfurization and purification areas, generator rooms, and locations

where confined-space work is frequent. Alarm signals should be connected to the central control system to enable continuous monitoring and linked early warning for abnormal gas concentrations, pressure, temperature, and liquid level [32].

For projects with long operating periods or obvious equipment aging, a life-cycle management system should be established for critical equipment. Tanks, pipelines, valves, gas storage facilities, safety valves, lightning and static protection facilities, and explosion-proof electrical equipment should be regularly inspected, maintained, and assessed. The adoption of the Internet of Things, big data, and intelligent sensing technologies could help build safety management platforms covering monitoring, early warning, response, and review. Such measures can transform safety management from experience-based inspection to data-supported prevention. Previous research on IoT-based anaerobic digester monitoring has shown that decentralized remote monitoring can support continuous observation of operational conditions and improve the availability of management information for anaerobic digestion systems [33].

4.3. Enhance Personnel Competence and Safety Awareness

This pathway responds to M4, M5, M8, M9, and M10, linking training and institutional implementation with high-risk operation control and worker behavior. Personnel competence is a key variable in translating safety systems into practice. A hierarchical and role-specific training system should be established for enterprise managers, safety officers, operation and maintenance staff, and frontline workers. Enterprise managers should receive training on safety responsibility, legal liability, and safety investment requirements. Safety officers should focus on risk identification, hazard rectification, work permits, and emergency organization. Frontline workers should be trained in biogas properties, hydrogen sulfide hazards, standardized operation, personal protection, and emergency response.

Training should be integrated with assessment and certification. Key positions, including electricians, welders, and workers involved in confined-space operations, should strictly comply with qualification management and annual retraining. Emergency drills should shift from formal exercises to scenario-based practical drills. High-consequence scenarios such as biogas leakage, fire and explosion, confined-space poisoning or asphyxiation, and unprotected rescue attempts should be regularly practiced. This is particularly important because accident evidence from biogas plants indicates that maintenance errors, operational errors, and inadequate personal protection are closely associated with accident occurrence and severity [9]. Drill evaluations should be used to revise plans, improve equipment configuration, and close the loop between exercises and real risk reduction.

4.4. Establish Sustainable Funding Mechanisms

This pathway directly responds to M1, one of the strongest source-level drivers, by ensuring that safety investment can be sustained throughout the project life cycle. Insufficient safety investment is a practical constraint for many private enterprises and projects with weak economic performance. A diversified funding mechanism combining government incentives, enterprise investment, and green finance should be explored. Project operators that actively install gas monitoring and alarm systems, upgrade explosion-proof electrical equipment, provide confined-space safety equipment, or replace aging facilities may receive project subsidies, interest-subsidized loans, or green financial support [34,35]. Green finance and governance effectiveness have been shown to play important roles in linking renewable energy investment with carbon-emission reduction, suggesting that financial instruments can also support the safer and more sustainable operation of renewable-energy infrastructure [36]. In the context of biogas projects, such instruments could be extended from capac-

ity expansion and emission reduction to safety-related upgrading, including monitoring systems, explosion-proof equipment, emergency supplies, and confined-space protection.

These funding instruments should be interpreted as evidence-informed governance proposals rather than direct outputs of the DEMATEL-ISM matrix. Their implementation would require clear eligibility criteria, responsible agencies, audit procedures, and performance-based conditions to avoid unintended incentives such as subsidy dependence or symbolic equipment procurement without effective maintenance.

A special fund for biogas project safety management may also be established. Such a fund could support major hazard rectification, renewal of critical safety equipment, emergency rescue supplies, systematic personnel training, and the development and promotion of safety technologies. For projects with weak safety foundations but important regional organic waste treatment functions, financial support should be combined with regulatory constraints to guide gradual improvement and prevent safety investment from being continuously compressed by operating pressure. From a sustainability perspective, stable safety investment is not a cost burden alone; it is a prerequisite for reliable waste treatment, renewable energy production, and long-term public acceptance. Therefore, financing mechanisms for biomethane projects should not be limited to capacity expansion or energy-output improvement, but should also include investment in safety barriers, monitoring systems, emergency preparedness, and workforce competence.

4.5. Integrated Process-Stage and Cost-Sensitive Governance Implications

The results suggest that governance recommendations should be implemented through both systemic priorities and process-stage priorities. The DEMATEL-ISM model identifies upstream governance and investment drivers, whereas the process-stage analysis clarifies where these drivers are translated into concrete safety barriers. For example, unclear regulatory responsibilities may appear operationally as inconsistent inspection requirements for gas holders, desulfurization units, generator rooms, and confined-space entry; insufficient safety investment may appear as missing fixed monitoring, aging explosion-proof equipment, inadequate ventilation, or insufficient rescue equipment.

Therefore, a staged governance strategy is needed. At the design and upgrading stage, high-consequence units should receive priority for fixed monitoring, explosion-proof design, corrosion control, and pressure protection. At the operation and maintenance stage, work permits, gas testing, ventilation, personal protection, and rescue preparation should be treated as mandatory control points. At the financing and supervision stage, subsidies or green-finance instruments should be linked to verified safety-barrier performance rather than to equipment purchase alone. This cost-sensitive interpretation helps make the proposed solutions more implementable and reduces the risk of symbolic investment without effective operation and maintenance.

This interpretation also complements existing sustainability and process-safety studies. Compared with HAZOP and bow-tie analysis, which usually focus on scenario-specific hazard identification and barrier visualization, the DEMATEL-ISM approach highlights cross-factor causal influence and governance-level transmission. It is therefore useful for identifying upstream management and institutional drivers, but it does not replace layers of protection analysis, quantitative risk assessment, or other methods designed to quantify accident probabilities, barrier failure probabilities, or consequence severity. Life-cycle and biomethane studies mainly emphasize environmental performance, energy substitution, and carbon reduction, while process-safety approaches emphasize hazard identification, barrier performance, and human-organizational reliability. The present study bridges these perspectives by treating safety as a practical enabling condition for the continuous and

socially acceptable operation of renewable-energy infrastructure, rather than as a directly measured carbon or energy-performance outcome.

5. Conclusions, Limitations, and Future Work

This study investigated five very large-scale biogas (biomethane) projects in Shanxi Province and analyzed their safety-risk causation using an integrated DEMATEL-ISM approach. The main conclusions are as follows.

First, the investigated projects showed a structural imbalance in safety management. Although all sampled projects had established basic safety management documents, only 20% had scenario-specific emergency response plans. The compliance rate of explosion-proof electrical equipment, the configuration rate of fixed monitoring and alarm systems for combustible and toxic gases, and the effective operation rate of forced ventilation facilities were 40%, 60%, and 40%, respectively. The coexistence of formal institutional completeness and weak operational implementation represents the central challenge in current safety management.

Second, DEMATEL-ISM analysis showed that M1 (insufficient enterprise safety investment) and M2 (unclear external regulatory responsibilities) were the key root causes of risk propagation, while M3 (weak awareness of enterprise safety responsibility) strengthened the driving effect. M4 (lack of a professional training system) and M5 (ineffective implementation of safety management systems) formed the management support layer; M6 (incomplete critical safety facilities), M7 (equipment aging and insufficient maintenance), and M8 (ineffective emergency drills) formed the system failure layer; and M9 (inadequate control of high-risk operations) and M10 (unsafe worker behavior) were direct manifestations.

Third, observable differences in safety management performance were found across ownership types in the sampled projects, although this finding should be interpreted cautiously because of the limited number of cases. In the sampled projects, state-owned enterprises showed relatively better foundations in training records, certification, institutional implementation, and emergency management, whereas private enterprises showed more prominent shortcomings in safety investment, facility configuration, and emergency capability. These observations suggest that project operators with weaker safety investment and implementation capacity should receive differentiated supervision and targeted assistance.

Fourth, safety governance of very large-scale biogas projects should shift from reactive correction at the operational end to a safety–sustainability governance framework integrating regulatory foundation, technological barriers, human competence, and financial sustainability. This framework corresponds to four pathways: improving policies and standards, strengthening technological support, enhancing personnel competence, and establishing sustainable funding mechanisms.

Fifth, the process-stage analysis indicates that high-consequence risks are concentrated in gas generation, gas storage, gas purification, energy utilization, digestate handling, and confined-space maintenance. Safety investment should therefore be prioritized according to risk consequences and cost burden by combining immediate operational improvements with staged upgrading of high-cost safety barriers.

This study has several limitations. The sample size was limited to five projects in Shanxi Province, and the DEMATEL expert-scoring process may still contain subjective judgment. Future research should expand the sample size, incorporate accident data, obtain direct influence matrices from a broader expert panel, and conduct dynamic risk simulation to improve the robustness and generalizability of the model. The cost-related analysis was qualitative and based on relative cost-burden categories rather than project-specific monetary accounting. Future studies should integrate verified cost data with safety-performance indicators to support quantitative cost–benefit analysis.

In particular, the observed ownership-related differences should be further verified using a larger sample, and the proposed safety–sustainability framework should be tested together with measured indicators of energy performance, greenhouse-gas mitigation, operational reliability, and economic sustainability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18168213/s1, Table S1. Inclusion criteria and anonymized project-level characteristics; Table S2. Assessment criteria for safety-status indicators; Table S3. Case-level results underlying Table 1; Table S4. Factor-development process, operational definitions, and supporting evidence; Table S5. Anonymized expert profiles; Table S6. Expert agreement, dispersion, and leave-one-expert-out stability; Table S7. Direct influence matrix A; Table S8. Normalized direct influence matrix D; Table S9. Total influence matrix T; Table S10. Adjacency matrix B at $\lambda = 0.06$; Table S11. Reachability matrix M at $\lambda = 0.06$; Table S12. Threshold sensitivity results; Table S13. Anonymized plant-level strategies, similarities, and differences; Table S14. Process-stage risk distribution and cost-sensitive control priorities; Table S15. Qualitative cost-burden classification used in the additional analysis.

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