

# Reconstructing University Laboratory Risk Governance: A Framework Based on the Dual Prevention Mechanism

Yanfei Chai<sup>1</sup>, Xin Su<sup>1</sup>, Pengfei Zhai<sup>2\*</sup>

1. Office of State-owned Assets Management, Office of Laboratory Management, Yancheng Teachers University, Yancheng 224007, China
2. School of Marine and Biological Engineering, Yancheng Teachers University, Yancheng 224007, China

\* E-mail of the corresponding author: [zhaipf@yctu.edu.cn](mailto:zhaipf@yctu.edu.cn)

## Abstract

Traditional laboratory safety governance has long relied on reactive, post-incident responses, making it ill-suited to the dynamic research risks arising from the convergence of interdisciplinary studies, novel reagents, and large-scale shared instruments. Guided by the policy orientation of shifting public safety governance toward proactive prevention, this paper theoretically deconstructs the Dual Prevention Mechanism in the industrial sector and adapts it to the research context, proposing an integrated governance reconstruction framework centered on proactive risk immunity. It further establishes a seven-step, full-lifecycle closed-loop system encompassing comprehensive identification, quantitative assessment, tiered control, multi-dimensional inspection, tiered governance, data feedback, and iterative optimization. Through field investigations across multiple universities, this study identifies five key barriers to implementation: institutional friction, cognitive barriers, technological deficiencies, insufficient inter-departmental coordination, and a lack of systemic resilience. Accordingly, it proposes a systematic implementation pathway along four dimensions: grid-based organizational accountability, a smart digital infrastructure, an intrinsic safety culture, and the upfront integration of safety into research workflows. This study elucidates the mechanism of the bidirectional coupling reinforcement loop between tiered risk control and hidden danger investigation and remediation, providing a theoretical framework and a replicable practical paradigm for the proactive intrinsic safety construction of laboratories in universities and research institutes.

**Keywords:** Laboratory Safety Governance; Proactive Safety; Dual Prevention Mechanism; Hierarchical Risk Control; Closed-Loop Management of Hidden Dangers; Reconstruction of Governance System

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## 1. Introduction

The rapid expansion of scientific research activities and booming interdisciplinary integration in higher education institutions have fundamentally transformed the operational characteristics of modern laboratories <sup>[1]</sup>. Current laboratory environments are featured with diversified hazard sources, iteratively updated experimental projects, frequent personnel mobility, and superimposed compound risks, which pose substantial challenges to conventional laboratory safety governance <sup>[2]</sup>. The increasingly frequent use of hazardous chemicals, operation of special equipment, and execution of specialized experimental procedures have led to a continuous rise in hidden and coupled safety risks <sup>[3]</sup>. Meanwhile, the traditional passive response model, characterized by an overemphasis on emergency response at the expense of early warning, has resulted in inadequate risk control and the recurring resurgence of hazards, rendering it ill-suited to meet the demands of modern scientific research development <sup>[4]</sup>.

National and educational authorities have continuously issued policies on laboratory safety regulation <sup>[5,6]</sup>, explicitly calling for a shift in safety management from post-incident emergency response to proactive prevention and routine control, and for leveraging scientific and digital governance tools to solidify the bottom line of research safety. Against this backdrop, innovating traditional governance paradigms and establishing a modern risk governance system characterized by proactive anticipation and closed-loop iteration have become core imperatives and inevitable trends in safety development for universities and research institutes.

## 2. Current Status and Key Transformation Issues of Safety Risk Management in University Laboratories.

Laboratories serve as the core frontier of original innovation, and their safe and stable operation constitutes a fundamental prerequisite for ensuring the sustainable development of scientific research. In recent years, safety incidents have occurred frequently across Chinese universities, including hazardous chemical fires, biological contamination, high-pressure gas cylinder explosions, and electrical short-circuit fires [7,8]. Statistical analysis of 112 typical incidents reveals that over 90% of safety hazards stem from long-term unidentified latent risks, as well as residual risks arising from the failure of control measures, while extreme sudden accidents account for only a minimal proportion [9]. Currently, laboratory safety management in China exhibits a typical "stimulus-response" reactive operational model, accompanied by three structural deficiencies [10,11].

First, risk governance suffers from temporal lag, resulting in management gaps in addressing silent coupled risks. During accident-free periods, safety resources are inadequately allocated, risk registers remain static for years with minimal updates, and attention is confined to surface-level visible hazards. Currently, there is a lack of proactive identification tools for composite low-probability, high-consequence risks formed by the superposition of multiple reagents, equipment, and operations, resulting in an overall backward shift of the risk defense chain and an inability to intervene at the incipient stage of hazard emergence. Second, governance resources fluctuate in a pulsed manner, and routine prevention and control are absent. After accidents occur, comprehensive campaign-style rectifications and institution-wide inspection and accountability are launched; after a short period of high-intensity management, resources rapidly revert to a low-efficiency management norm, leading to fragmented and discontinuous safety investment. Third, governance responsibilities are fragmented across multiple stakeholders, resulting in a disconnect between research activities and safety management. Functional boundaries separate research, asset and equipment management, security, and logistics departments; risk identification, hazard inspection, and rectification review belong to independent operational modules, lacking a unified and coordinated closed-loop process. This leads to recurring rectification failures and persistent hazards that remain unresolved despite repeated remediation efforts. Meanwhile, risk control has not been embedded into the entire workflow of project approval, reagent requisition and experiment implementation, which creates the inherent contradiction of "disconnect between scientific research and safety". Top-level policies continuously promote the transformation of safety management models. *Recommendations of the Central Committee of the Communist Party of China for Formulating the 15th Five-Year Plan for National Economic and Social Development* clarifies the general requirement for transforming public safety toward proactive prevention [5]. *Document No. 11 [2016] of the Office of the State Council Work Safety Commission* establishes the dual prevention mechanism as the core instrument for proactive risk prevention and control [6]. The Ministry of Education's *Measures for the Tiered and Categorized Management of Laboratory Safety in Higher Education Institutions (Trial)* and *Opinions on Strengthening Laboratory Safety in Universities and Colleges* require the establishment of a long-term control system featuring tiered risk classification and closed-loop hazard management, and the enforcement of safety responsibilities across all organizational levels [12, 13]. The core value of the dual prevention mechanism lies in shifting the safety defense frontier forward and constructing two progressive layers of defense-in-depth barriers, making it inherently well-suited to the requirements of proactive safety development.

A review of existing relevant studies reveals that current research outcomes exhibit obvious limitations. First, most studies directly transplant the industrial dual prevention framework into the laboratory context without scenario-specific adaptations for faculty-student mobility, dynamic experimental project cycles, and multi-disciplinary hazard heterogeneity, leading to limited practical fit [14, 15]. Second, existing studies predominantly focus on the construction of individual information platforms or the development of an individual risk-assessment model, lacking a systematic analysis from the perspective of governance paradigm reconstruction to address the underlying logic, multiple implementation barriers, and comprehensive implementation framework of the transition from passive management to proactive resilience [16,17]. Third, research on the coupling mechanism of bidirectional cyclical feedback between risk control and hazard investigation remains superficial; most studies regard the two as independent, segmented processes, overlooking the reinforcing loop value of continuous iterative optimization [18].

In response to the limitations of existing research, this study adopts "proactive safety" as the guiding principle and employs the dual prevention mechanism as the core instrument to reconstruct the laboratory risk governance system.

It focuses on addressing three key issues: first, clarifying the governance essence and bidirectional coupling mechanism of the dual prevention framework adapted to research settings; second, constructing a multi-dimensional integrated implementation framework encompassing organization, digital infrastructure, safety

culture and business procedures; and third, identifying multiple implementation barriers and proposing stratified and categorized breakthrough pathway, so as to build a new proactive safety governance system featured by proactive prevention, dynamic revision and self-adaptive iteration.

### **3. Architecture and Operational Mechanism of the Dual Prevention Mechanism for Proactive Safety in University Laboratories.**

The dual prevention mechanism is not a simple superposition of two separate links, namely risk management-control and hazard investigation. Instead, it constitutes a complete and organic governance system consisting of a pre-defense layer, a process restoration layer and a cyclical optimization layer, and serves as the core instrument for enabling laboratories to transition from reactive response to proactive immunity <sup>[19]</sup>.

#### *3.1 The First Prevention Layer: Risk Hierarchical Control — A Proactive Safety Foresight Engine*

Core Objective: To intervene on all-element hazard sources before accident triggers fully materialize, thereby blocking the transformation of risks into hidden dangers. The operational logic unfolds through four progressive procedures.

First, comprehensive dynamic risk scanning: integrating three identification tools, namely task analysis, facility condition assessment, and Job Hazard Analysis (JHA). It covers seven dimensions: experimental operating procedures, special equipment, hazardous chemicals, high and low temperature equipment and radiation facilities, environmental conditions, human behaviors, and organizational management. Distinct from the static identification used in fixed industrial production lines, it establishes a project synchronized updating mechanism whereby new projects trigger concurrent risk identification upon initiation, thereby maintaining a dynamic risk inventory and mitigating the risk of overlooking cross-coupling hazards <sup>[20]</sup>.

Second, three dimensional quantitative risk grading: building upon the traditional two dimensional risk matrix, this approach incorporates exposure duration and personnel susceptibility as additional dimensions, and employs the Risk Priority Number (RPN) for semi-quantitative assessment. Risks are classified into four tiers: red (critical), orange (major), yellow (moderate), and blue (low), with differentiated control intensities aligned to university laboratory grading standards, thereby overcoming the distortion inherent in single dimension probability consequence grading.

Third, gradient tiered control measures: strictly adhering to the hierarchy of controls, namely elimination, substitution, engineering isolation, administrative management, and personal protective equipment, in order of priority <sup>[21]</sup>. Red-level (critical) risks are subject to university level designated oversight with dedicated management, restricted access to authorized personnel, and mandatory specialized review; orange-level (major) risks are managed at the faculty level with dual person staffing and monthly specialized inspections; yellow-level (moderate) and blue-level (low) risks are managed at the routine laboratory level through routine oversight, with streamlined procedures to reduce the burden on front line personnel. A standardized list of control measures corresponding to each risk level is compiled simultaneously.

Fourth, comprehensive visualization of risk information: establishing four types of information notification carriers, namely a four color laboratory risk distribution map, individual room hazard source notification cards, equipment safety signboards, and reagent storage labels, supported by basic safety training, so as to eliminate blind spots in risk perception among teachers and students <sup>[22]</sup>.

#### *3.2 The Second Prevention Layer: Hazard Investigation and Remediation — A Proactive Safety Self-Adaptive Repair System*

Risk grading and control provides standardized defensive measures. Nevertheless, affected by operational deviations, equipment aging and weakened implementation, control measures tend to generate failure gaps, namely safety hazards. The core function of this layer is to continuously monitor and repair damages to the first line defensive barrier, thereby preventing hazards from escalating into accidents <sup>[23,24]</sup>.

First, standardized definition of hazards: in accordance with *the Work Safety Law*, hazards are defined as safety gaps arising from the absence, deviation, or failure of risk control measures. Hazard investigation is, in essence, a compliance audit of the effectiveness of control measure implementation. Investigation standards are uniformly based on the pre-established risk list, addressing the pain points of non-standardized and highly subjective traditional inspections <sup>[25]</sup>. Hazards are classified into three grades according to hazard severity: major, ordinary and minor, with differentiated rectification timelines and supervision levels assigned correspondingly.

Second, a "three-level, three-type" three-dimensional inspection network: vertically, three levels of responsible

entities are established across the university, departments, and laboratories (research groups); horizontally,, three inspection scenarios are defined: daily patrols, special inspections and comprehensive supervision. Daily patrols are carried out by safety officers on a daily basis; monthly special inspections are performed for high risk fields such as hazardous chemicals, gas cylinders and biosafety <sup>[26]</sup>; and multi-departmental comprehensive supervisions are conducted on a quarterly basis. Mobile-based information tools are leveraged to enable automatic task push notifications, on site photographic documentation, and real time hazard reporting <sup>[27,28]</sup>.

Third, a six-step closed-loop hazard clearance process: a complete closed-loop chain is established, comprising hazard identification, severity assessment, tiered alerting, categorized rectification, on-site verification, and case closure with sign-off. Major hazards are subject to university level designated oversight, with suspension of related experiments and provision of dedicated funding and expert technical support; general hazards shall be rectified within seven working days; and minor hazards are addressed on the spot. Documents and images of the whole process are permanently archived in the digital platform to realize full-process traceability of responsibilities <sup>[18,29]</sup>.

### *3.3 Mechanism of Bidirectional Coupling-Enhanced Cyclic Reinforcement*

The two elements form a self-optimizing loop characterized by dialectical symbiosis and bidirectional empowerment, which constitutes the core innovation for the system's self-adaptive iteration. On the one hand, the risk grading and control checklist serves as a standardized roadmap for hazard investigation, unifying inspection content and judgment thresholds to eliminate inspection arbitrariness. On the other hand, massive hazard rectification data act as a calibrator for the control system. Big data analysis is adopted to identify frequently failed control measures and omitted hazard sources, retroactively review deviations in risk identification and grading assessment, dynamically revise risk lists and adjust control schemes. Repeated cycles of the two drive continuous upgrading of the safety governance system and fundamentally overcome the drawbacks of conventional static and rigid frameworks that fail to adapt to emerging scientific-research risks.

## **4. Integrated Implementation Framework and System Construction for Proactive Safety in University Laboratories.**

To address the challenge of the dual prevention mechanism being reduced to superficial implementation and formalistic operation, this study comprehensively reconstructs the traditional management system from four dimensions: organizational system, digital infrastructure, safety culture, and scientific research business process <sup>[30]</sup>.

### *4.1 Reconstruction of Institutional Safeguards: A Grid-Based, Vertically and Horizontally Integrated Responsibility Network*

#### *4.1.1 Four-tier vertical responsibility chain*

The university-level Party and administrative leaders serve as the primary responsible persons, overseeing top-level design and resource guarantee; The deans act as the direct managers of their respective units; Laboratory directors and project principal investigators are the primary on-site implementers, and all teachers and students bear responsibility for post operation safety. Differentiated safety responsibility letters are signed at the four hierarchical levels. The implementation effectiveness of the dual prevention mechanism is incorporated as a mandatory indicator in performance appraisal, project fund review, and professional title evaluation.

#### *4.1.2 Horizontal Multi-Department Coordination Mechanism*

A monthly joint meeting is set up involving scientific research, assets, equipment, security, logistics, academic affairs and safety experts. A special joint-handling task force is established for cross-domain hazards such as hazardous chemical procurement, hazardous waste disposal, and shared instrument safety to break down administrative barriers.

#### *4.1.3 Minimum-Grid Responsibility Allocation*

Taking individual laboratory rooms and complete equipment units as grid cells, dedicated grid safety officers are assigned to exclusively oversee risk updates, daily inspections, and hazard tracking within their designated grids, thereby eliminating management blind spots across the entire scope.

### *4.2 Reconstruction of Digital Infrastructure: Smart Dual-Prevention Safety Hub*

Purely manual ledgers are unable to support the demands of dynamic risk updates and massive volumes of closed-loop data. An integrated intelligent platform is therefore established, comprising four core modules:

**Dynamic Risk Database Module:** Incorporating standardized identification templates, hierarchical algorithms, and a control measures library, this module enables online risk assessment for new projects, one-click updating of equipment and reagent change lists, and automatic highlighting of coupled high-risk points.

**Mobile Hazard Closed-Loop Module:** Automatically dispatching inspection tasks, this module supports on-site image uploading and automatic hazard classification, pushes rectification assignments to responsible personnel by severity level, and triggers automatic escalation alerts for overdue hazards.

**Hazard Big Data Analytics and Early Warning Module:** Integrating historical hazard records, risk levels, and operational logs to identify evolutionary patterns, this module predicts high-risk operational periods and failure-prone points, enabling proactive early warning.

**Full-domain One-map Safety Visualization Module:** The large-screen display providing real-time visualization of laboratory distribution, risk levels, unresolved hazards, and training completion status, thereby providing data support for management decision-making <sup>[31]</sup>.

#### *4.3 Reconstruction of Safety Culture: Achieving the Endogenous Transformation toward "I Want Safety"*

Regulations and technology serve only as external constraints; endogenous participation motivation is the foundation for sustainable operation. Safety culture is therefore reshaped across three layers:

**Tiered Immersive Thematic Training:** The principles of dual prevention and hazard identification methods are incorporated into mandatory courses for new students, newly-recruited staff, and thesis proposal defense. Immersive teaching approaches are adopted, including VR accident scenario simulations, real-scene hazard training, and case review sessions. An advanced training program is offered to safety officers for systematic study of professional methods such as risk matrices and RPN assessment <sup>[2, 32]</sup>.

**Positive Incentives for Active Prevention and Control:** A "Safety Golden Ideas" reward and a hazard reporting point redemption system are established, where accumulated points can be exchanged for laboratory consumables or applied toward merit evaluation bonuses, thereby broadening the sources of risk clues.

**Non-Punitive Near-Miss Reporting Mechanism:** Proactive reporting of minor hazards and operational errors is used solely as a basis for system optimization and is exempt from accountability; accountability is imposed only for concealment and refusal of rectification, so as to remove teachers' and students' concerns about reporting.

#### *4.4 Integration of Safety Control into Research Processes: Embedding Safety Governance at the Front End Across the Entire Research Lifecycle*

To resolve the "two separate tracks" disconnect at the source of operations, the risk assessment report serves as a prerequisite for three key access points: research projects without risk assessments shall not be approved or funded; hazardous chemical procurement and special equipment activation require verified records of risk notification and training; and project closure review shall verify risk updates and closed-loop hazard rectification records throughout the project cycle as mandatory acceptance criteria. At the institutional level, this mechanism compels all personnel to implement dual prevention measures.

### **5. Implementation Barriers and Optimization Pathways of the Dual Prevention Mechanism in University Laboratories.**

Based on field visits to multiple universities, in-depth interviews with safety management personnel, and cross-comparison of existing practical literature, four core inhibiting factors are identified, with corresponding implementation paths formulated <sup>[33]</sup>.

#### *5.1 Cognitive Barriers and Formalism*

Researchers perceive the dual prevention mechanism as an additional administrative burden, resulting in a disconnect between record-keeping and on-site management. Breakthrough pathways: linking safety performance to the access permission of research resources; institutionalizing regular on-site engagement by university and departmental leaders in grid-based risk identification; conducting targeted inspections to benchmark records against on-site conditions, and reducing research resource allocation for units found engaging in false rectification.

#### *5.2 Deficiencies in Front-line Professional and Technical Capacity*

Teachers and students lack standardized risk assessment tools, and risk classification of complex, cross-disciplinary experiments is highly challenging. Breakthrough Paths: developing lightweight templates for chemistry, biology, and electromechanical disciplines, enabling menu-based selection of control measures;

establishing a multidisciplinary university-level safety expert team to conduct on-site diagnostics; and compiling an online case library and hands-on instructional short videos for self-directed learning <sup>[34, 35]</sup>.

### *5.3 Low Efficiency of Cross-department Collaborative Governance*

Disputes over responsibilities for compound hazards lead to repeated rebounds in rectification. Breakthrough Paths: institutionalizing monthly joint coordination meetings and establishing a cross-departmental joint hazard management ledger; setting up special guarantee funds for laboratory safety; and conducting quarterly multi-department joint inspections with coordinated rectification follow-up.

### *5.4 Insufficient System Resilience and Weak Adaptability to Emerging Risks*

The traditional framework is applicable only to conventional experiments, with lagging updates in risk identification and classification for emerging cross-disciplinary fields and novel reagent hazards. Breakthrough Paths: conducting annual reviews of system effectiveness and updating identification and classification standards; predicting potential coupled risks relying on big data early-warning models; and streamlining the temporary risk assessment process for new projects while reserving flexible control mechanisms <sup>[29]</sup>.

## **6. Conclusion**

Reconstructing a proactive laboratory risk governance system based on the dual prevention mechanism represents a systematic transformation of the traditional reactive post-incident management model, encompassing multi-dimensional upgrades across management logic, organizational accountability, digital technology, safety culture, and research business processes. The four-dimensional integrated framework developed in this study clarifies the bidirectional cyclic coupling mechanism of dual prevention, identifies multiple implementation barriers, and provides hierarchical solutions. It realizes three major paradigm shifts: the transformation from linear segmented management to cyclic iterative governance, from decentralized departmental control to grid-based collaborative governance, and from experience-based manual response to data-driven proactive early warning. This research provides a complete theoretical and practical scheme for the intrinsic safety construction of laboratories in universities and research institutions <sup>[36]</sup>.

Looking ahead, with the iteration of digital technologies, the proactive safety system will evolve toward three major directions: intelligence, high resilience, and full-domain coverage. Integrating Internet of Things (IoT) perception and visual large models enables automatic risk identification and real-time hazard perception <sup>[37]</sup>; The improved self-adaptive adjustment mechanism can adapt to unknown and emerging scientific research risks; Furthermore, dual prevention management and control will be extended to off-campus cooperative laboratories and field scientific research sites to construct an integrated full-domain proactive safety defense line, so that the highly resilient safety governance system can support the high-quality development of scientific and technological innovation <sup>[38,39,40]</sup>.

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