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Research on the Construction of Laboratory Safety Culture in Chinese Universities: Current Status, Challenges, and Development Paths

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Abstract: The development of a laboratory safety culture in universities is a crucial step to tackle the complexity of managing hazardous sources and to foster the evolution of safety management. Drawing on the INSAG framework, this study establishes a four-dimensional model that encompasses spiritual, institutional, behavioral, and material aspects. It examines international models, including those of the National University of Singapore and the U.S. EHS, and investigates structural conflicts within Chinese universities related to safety awareness, institutional enforcement, and behavioral dissemination by synthesizing data from 137 accidents. The study suggests a collaborative four-dimensional approach to overcome management obstacles and establishes a digital safety culture paradigm, offering insights for the modernization of university safety governance and positively contributing to the integration of global standardization with local practices.

Keywords: university laboratories; safety culture construction; four-dimensional analysis model; international comparison.

1. Introduction

Laboratories are essential spaces for scientific research and teaching within universities. The level of their safety governance directly impacts the protection of teachers' and students' lives and health, the orderly progression of scientific research activities, and the high-quality development of higher education. In recent years, as national investment in technological innovation has continuously increased, the scale of university laboratories, the complexity of their equipment, and the variety of hazard sources have all experienced significant growth [1]. Statistics reveal that between 2004 and 2024, a total of 137 laboratory safety incidents occurred at Chinese universities, resulting in 177 injuries and 19 fatalities. The primary causes of these incidents include a lack of safety awareness, insufficient operational standards, and gaps in management systems.[2-4].

Academic research, grounded in the "2-4" model of accident causation, suggests that the absence of a safety culture is the fundamental cause of systemic risks [5]. This finding has spurred a transition in safety management paradigms, moving from "passive prevention" at the technical level to "active safety" at the cultural level. The safety culture theoretical framework, introduced by the International Nuclear Safety Advisory Group (INSAG) in 1991, offers an interdisciplinary research perspective for addressing laboratory safety governance issues [6]. Despite domestic research establishing a "spiritual-institutional-behavioral-material" four-dimensional analysis model, there continue to be dual challenges in theoretical interpretation and practical innovation, including cognitive gaps, deviations in institutional implementation, and the intergenerational transmission of behaviors. [7-8].

From an international comparative perspective, this study systematically explores the structural contradictions in the construction of safety culture within Chinese universities. It does so by analyzing advanced models, such as the three-level responsibility network of the National University of Singapore and the full-life-cycle management of U.S. EHS, in conjunction with empirical data analysis of 137 accidents. The study proposes, for the first time, a "digital safety

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culture" development paradigm. The aim is to provide theoretical support and practical paths for building a laboratory safety governance system with Chinese characteristics.

2. Connotation and System Architecture of Laboratory Safety Culture

Table 1: Four-Dimensional Hierarchical System of Laboratory Safety Culture.

Dimension	Performance
Spiritual Culture	As the core, it embodies safety values, risk perception, and sense of responsibility
Institutional Culture	As the guarantee, it covers rules, regulations, management processes, and assessment mechanisms
Behavioral Culture	As the external manifestation, it reflects operational norms, habit formation, and emergency response capabilities
Material Culture	As the foundation, it includes safety facilities, environmental conditions, and technical equipment

2.1 Theoretical Framework of Core Connotation

The International Nuclear Safety Advisory Group (INSAG) first introduced the concept of safety culture in 1986 and provided a detailed theoretical framework in the INSAG-4 report, published in 1991. Laboratory safety culture is an integrated system that encompasses values, behavioral norms, institutional systems, and material conditions, all of which are developed within the scientific research and teaching environment. Its aim is to ensure personnel safety, the reliable operation of equipment, and environmental sustainability. This concept transcends the boundaries of traditional technical management by emphasizing a shift in governance paradigms from passive prevention to proactive safety, achieved through cultural influence.

Domestic academic circles generally agree that laboratory safety culture comprises four dimensions [7-8]: spiritual culture, which is the core, embodying safety values and awareness; institutional culture, which acts as a safeguard, encompassing rules, regulations, and management processes; behavioral culture, which is the external manifestation, reflecting operational norms and habits; and material culture, which forms the foundation, including safety facilities and environmental construction. This division is consistent with the core principles of INSAG theory and offers a structured analytical framework for the development of safety culture.

2.2 Synergistic Effects of Mechanisms

The mechanism of laboratory safety culture is reflected in its potential guiding function, rigid normative function, consensus coordination function, and continuous innovation function.

Table 2: Mechanisms of Laboratory Safety Culture

Function	Connotation
Guiding Function	Shaping through safety values to guide personnel in forming risk prediction thinking
Normative Function	Defining behavioral boundaries and operational standards through institutional constraints
Coordination Function	Promoting the adaptation of management processes and scientific research activities through consensus culture
Innovation Function	Driving the upgrading of material security systems through the iteration of safety technologies

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Empirical studies by scholars, including Peng Huasong, indicate that when safety culture is deeply embedded in laboratory operations, personnel's safety behaviors evolve through three stages: from "passive compliance" to "active practice," and subsequently to "value identification." This results in a significant reduction in accident rates [9-10]. The transformation in behavior originates from the reshaping of individual cognition by culture: spiritual safety culture enhances safety awareness through education and training; institutional culture clarifies behavioral boundaries through process standardization; behavioral culture reinforces safe operations by fostering habits; and material culture provides a safety foundation through facility guarantees. These four aspects interact to create a governance closed loop through dynamic coupling: spiritual culture guides institutional design, institutional culture standardizes behavioral development, behavioral culture informs material needs, and material culture supports spiritual identity, collectively forming an ecosystem for laboratory safety governance.

From a psychological perspective, this transformation adheres to the principles of cognitive restructuring: altering risk perception through safety training (cognitive stage), eliciting emotional resonance via case education (emotional stage), and establishing behavioral inertia through repeated standardized operations (behavioral stage). The National University of Singapore (NUS) employs a training model that combines "online courses, practical drills, and psychological intervention," which has resulted in a safety compliance rate exceeding 95% among new entrants, thus validating the efficacy of this approach [11-12].

3. Current Status of Laboratory Safety Culture Construction at Home and Abroad

3.1 Advanced Foreign Experiences and Typical Models

The multi-level management system of the National University of Singapore (NUS) is internationally recognized as an exemplary management model. Its organizational structure, meticulously designed to include core institutions such as the Institutional Laboratory Safety Committee (ILSC), Office of Safety, Health, and Environment (OSHE), and University Health Centre (UHC), constructs a three-tiered responsibility network. This network features overall responsibility by the president, collaborative division of labor by functional departments, and specific implementation by laboratories. In terms of institutional construction, NUS has established a rigorous regulatory system that covers hazardous chemical management, risk assessment, and emergency response. Particularly in risk assessment, NUS innovatively introduced a "severity-probability" matrix model, quantifying risk levels from low to high and adopting targeted control measures based on specific scores, ensuring that the pre-intervention rate for high-risk experiments is close to 100%.

Institutions of higher education in the United States underscore the profound integration of professional expertise and information technology within the realm of Environment, Health, and Safety (EHS) management. For instance, the University of California, Berkeley's EHS department not only employs safety experts with backgrounds in chemistry, biology, and radiation but also ensures that these professionals are equipped to offer tailored safety solutions for laboratories through systematic training and ongoing professional development. Additionally, Berkeley leverages sophisticated information platforms, such as LabVantage, to manage the full lifecycle of hazardous chemicals, from procurement and storage to usage and disposal, thereby markedly enhancing safety management efficiency. In contrast to domestic universities that depend on administrative systems for safety management, U.S. universities prioritize a management system characterized by a professional division of labor. This distinction significantly influences the efficacy of safety culture development.

Institutions of higher education in Germany underscore the principle of "shared responsibility" within their safety culture development frameworks. The Technical University of Munich thoroughly embeds safety culture into its research ethics evaluation system, explicitly stating that

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Principal Investigators (PIs) are primarily accountable for laboratory safety and endowing each laboratory member with "safety veto power." This ensures that safety culture permeates every aspect of the research process.

The University of Tokyo in Japan employs "5S management" (seiri, seiton, seiso, seiketsu, shitsuke), and the accident rate in chemical laboratories has significantly decreased for consecutive years through standardized processes. Its "waste classification visualization board" has been recognized by ISO as a classic case of safety culture.

McGill University in Canada has implemented a "safety partner system," which mandates that experimenters work in pairs for mutual supervision. This system has significantly reduced the rate of violations. Additionally, the supportive "safety mutual assistance APP" facilitates real-time reporting of potential hazards and includes a point reward mechanism.

3.2 Exploration and Practice in Chinese Universities

The primary tasks of universities involve institutional construction and organizational structure optimization. Shanghai Ocean University has established a "Five-One Project" safety culture system, which encompasses responsibility systems, rules and regulations, operation mechanisms, education systems, and safety facilities. The implementation of responsibility letters has solidified these responsibilities, leading to a significant decrease in the detection rate of laboratory hazards. Lanzhou University of Technology has developed a "three-level and nine-stage" responsibility system, breaking down management responsibilities vertically into three levels: university, college, and laboratory. Additionally, three horizontal responsibility positions have been established, creating a grid management matrix that allows for a detailed and clear delineation of safety responsibilities.

Innovative models of safety education and training are continually evolving. Hebei University incorporates ideological and political education into safety education courses, vividly demonstrating research missions through video cases and deeply analyzing the connotations of safety ethics. This approach effectively enhances students' risk identification capabilities and sense of responsibility. Fuzhou University, based on the accident causation theoretical framework, has constructed multi-dimensional evaluation indicators[14], including safety concept cognition, management system completeness, behavioral habit formation, and operational standardization. The university employs fuzzy mathematics methods to quantitatively evaluate the maturity of safety culture, providing a scientific basis for laboratory management optimization.

The integration of information technology with safety culture continues to deepen. Hangzhou Dianzi University has developed an intelligent laboratory safety management platform, which includes modules such as access control permissions, video inspections, and hazardous chemical tracking. It identifies hidden danger patterns through data analysis to enhance the accuracy of early warnings. Nankai University employs visual communication technology, utilizing mind maps to deconstruct processes and safety comics to illustrate protection points in professional laboratory education [15], thereby improving the memory efficiency of complex procedures and increasing the adherence to safety norms.

4. Practical Challenges in Laboratory Safety Culture Construction

4.1 Cognitive Biases at the Spiritual Culture Level

Weak safety awareness and fluke psychology remain major obstacles. Statistical analysis shows that most laboratory accidents stem from human negligence or intentional violations, such as failing to wear necessary protective equipment or simplifying operational processes [2]. For example, from 2001 to 2020, 113 laboratory safety accidents were reported in national universities, resulting in 99 casualties [1]. In addition, case analysis shows that safety accidents such as chemical leaks and explosions, fires, and personal accidents are caused by operators' negligence or non-compliance with safety regulations [2]. The root cause lies in insufficient awareness of safety risks: some

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researchers regard safety investment as a "research cost" rather than a "necessary prerequisite" and easily ignore safety norms under schedule pressure. Although a survey by a university shows that some project leaders believe that "safety training affects research efficiency," studies have shown that prioritizing laboratory safety does not affect research efficiency [4].

Significant hierarchical differences exist in safety culture identity. School management focuses on institutional improvement, laboratory directors emphasize operational norms, and front-line personnel pay attention to personal protection. Cognitive differences result in a "top-heavy, middle lukewarm, bottom cold" situation in safety culture construction. A questionnaire survey by a university shows that management's attention score to safety culture is significantly higher than that of front-line personnel, and this gap hinders the cohesion of safety culture. Cognitive biases not only weaken the implementation of safety systems but also lead to imbalanced allocation of safety resources.

4.2 Implementation Dilemmas at the Institutional Culture Level

The disconnection between rules and regulations and actual research needs is particularly prominent. Many universities directly apply industrial safety standards without fully considering the uniqueness of laboratories, such as "small batch, multiple varieties, and high variability." For example, a university stipulates that "the storage volume of hazardous chemicals shall not exceed 50L" but does not distinguish between ordinary chemicals and highly toxic chemicals, which often leads to conflicts between the actual needs of research work and safety regulations, thereby triggering frequent violations.

The failure of safety assessment and incentive mechanisms weakens execution. Currently, most universities link safety assessment with evaluation for excellence, but due to the lack of quantitative indicators, assessments often become a formality. Safety inspection records of a university show that most laboratories are rated as "basically qualified," but a considerable number of accidents in the same period resulted from "failure to implement assessment requirements." This "empty assessment" phenomenon significantly reduces the deterrence of the system.

4.3 Difficulties in Habit Formation at the Behavioral Culture Level

The intergenerational transmission of unsafe behaviors forms a vicious circle. New entrants usually acquire experimental operation skills through "observation-imitation." If senior personnel have irregular operation habits, such habits will quickly spread to new members. A follow-up survey of a laboratory shows that the proportion of new members with similar violations in teams with the habit of "improper waste liquid disposal" is significantly higher than that in teams with standardized operations. Such "behavioral inertia" significantly prolongs the cycle of laboratory safety culture construction.

Insufficient emergency capabilities lead to the expansion of accident consequences. Although most universities organize regular emergency drills, most drills are still limited to a "formalized" level and fail to effectively simulate emergency response in real panic situations. The results of a practical drill test conducted by a university show that the proportion of people who can correctly operate fire extinguishers in a simulated environment of "thick smoke and strong noise" is significantly low. Such lack of key emergency capabilities makes it easy for initial accidents to evolve into major disasters.

4.4 Resource Constraints at the Material Culture Level

In the current safety management of university laboratories, the uneven allocation of safety facilities is relatively significant, and the investment in safety resources in key laboratories is significantly higher than that in ordinary laboratories. An empirical survey of provincial universities in a certain province shows that a considerable proportion of basic teaching laboratories are not equipped with emergency eye wash devices, significantly increasing the risk of experimental operations; the ventilation systems in some laboratories do not meet national mandatory standards,

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leading to the accumulation of harmful gases and posing a continuous threat to the health of experimenters. The lack of material guarantees seriously hinders the substantive construction of laboratory safety culture, making it difficult to truly implement it at the practical operation level.

The dilemma of renovating old laboratories also restricts the improvement of safety performance. Many university laboratory buildings were built in the 20th century, and their architectural structure design and fire-fighting facilities configuration cannot meet current safety standards. Such renovations involve complex engineering and technical problems such as structural reinforcement and pipeline system reconstruction, and require huge funds far beyond the affordability of universities, resulting in the long-term shelving of renovation plans and the continuous existence of safety hazards. This phenomenon is common in the university system, and the interweaving of fund shortages and complex engineering problems jointly restricts the overall improvement of laboratory safety levels.

5. Optimization Paths: Construction of Laboratory Safety Culture

5.1 Spiritual Culture: Cognitive Reconstruction from "Being Required to Be Safe" to "Wanting to Be Safe"

Constructing a hierarchical and classified safety education system is key. For management, it should focus on safety strategic planning and responsibility awareness cultivation, and adopt a "safety leadership training" model; for teachers, it should strengthen "research safety ethics" education and integrate safety culture into teacher ethics assessment; for students, it should develop "experiential" safety education courses, such as simulating dangerous scenarios using VR technology.

Creating safety culture brand activities to enhance penetration. Drawing on the experience of "Laboratory Safety Culture Month" at Huainan Normal University, activities such as safety knowledge competitions, hidden danger investigation contests, and safety micro-video creation can be carried out to transform boring safety knowledge into vivid cultural experiences. The implementation of these activities helps improve teachers’ and students’ safety awareness, thereby creating a strong safety culture atmosphere.

5.2 Institutional Culture: Mechanism Innovation from "Passive Compliance" to "Active Compliance"

Establishing a risk-based dynamic management system. Referring to NUS’s risk assessment matrix, laboratories are managed differently according to risk levels (low, medium, high): low-risk laboratories simplify inspection processes, while high-risk laboratories increase inspection frequency and are equipped with full-time safety officers. This dynamic management system can reasonably allocate safety resources according to the actual risk situation of laboratories and improve the efficiency of safety management.

Improving safety incentive and accountability mechanisms. Establishing a "safety points" system to convert compliant behaviors into redeemable points, such as using points to exchange for equipment usage priority; at the same time, implementing a "safety veto system" to directly link safety performance with professional title evaluation and project application.

5.3 Behavioral Culture: Habit Formation from "Individual Self-Discipline" to "Team Mutual Discipline"

Implementing a "safety partner system" to promote mutual supervision. Pairing experimenters to act as mutual safety supervisors, who can remind each other of violations and record them, with rewards given at the end of the month based on records. Tracking data shows that this system has significantly reduced the incidence of violations and significantly improved the team collaboration atmosphere. This system can give full play to the strength of the team, forming a good situation of mutual supervision and mutual promotion.

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Strengthening practical training of emergency capabilities. Changing the "performative" drill model to "scriptless" drills, with random setting of emergencies to test emergency responses. The "blind drill" test at Huainan Normal University shows that after three practical drills, the correct rate of personnel’s emergency disposal has significantly increased. Such "pressure training" can effectively improve safety response capabilities in real scenarios.

5.4 Material Culture: Technological Upgrading from "Basic Guarantee" to "Intelligent Early Warning"

Promoting intelligent transformation of safety facilities. Installing intelligent sensors to realize real-time monitoring of temperature, humidity, gas concentration, and equipment operation status, with automatic alarms for abnormal situations and linkage with ventilation and sprinkler systems. The introduction of intelligent monitoring systems has significantly improved the speed of safety response. In implementing intelligent transformation, it is necessary to consider the actual situation of different universities and formulate reasonable transformation plans.

Establishing a safety resource sharing platform. Integrating safety facility resources among universities in the region, such as co-building shared warehouses for hazardous chemicals and sharing emergency rescue teams, to reduce the safety investment pressure of small and medium-sized laboratories. The practice of Huainan Normal University shows that the efficiency of resource utilization has been significantly improved by building an integrated experimental resource sharing system.

6. Future Outlook: Development Trends of Laboratory Safety Culture in the Intelligent Era

6.1 Digital Transformation Drives Innovation in Safety Culture

With the popularization of technologies such as the Internet of Things and big data, the construction of laboratory safety culture will develop in the direction of digitalization and intelligence. Future safety management platforms can identify unsafe tendencies in advance through AI analysis of personnel behavior patterns; use digital twin technology to simulate laboratory operations and optimize safety layouts; and realize the immutability of safety records through blockchain technology to enhance regulatory credibility. Such "digital safety culture" will break through the time and space limitations of traditional management, achieving all-weather and all-round safety culture infiltration. Compared with traditional information management, digital safety culture emphasizes more on data analysis and application, as well as intelligent human-computer interaction.

6.2 Interdisciplinary Integration Expands Research Dimensions

Safety culture construction will incorporate more perspectives from psychology, sociology, behavioral science, and other disciplines. For example, applying the "nudge theory" of behavioral economics to design safety prompts, using group dynamics principles to optimize safety team building, and identifying key nodes in safety culture dissemination through social network analysis. Such interdisciplinary research will transform safety culture construction from experience-driven to theory-driven, enhancing its scientificity and effectiveness.

6.3 Safety Culture Co-construction from a Global Perspective

With the improvement of research internationalization, laboratory safety culture will present the characteristics of combining standardization and localization. On the one hand, international organizations such as ISO will promote the formulation of global standards for laboratory safety culture; on the other hand, countries will adjust implementation strategies according to cultural differences. Eastern culture tends to emphasize "collective responsibility," while Western culture

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focuses more on "individual rights." This difference provides an opportunity for the coexistence and development of safety culture construction in a unified framework.

7. Conclusion

The construction of laboratory safety culture in universities, as the cornerstone of high-quality development of scientific research and teaching, is not only crucial for achieving safety transformation but also a core path for addressing risks and ensuring the safety of teachers' and students' lives and property. Based on the "spiritual-institutional-behavioral-material" four-dimensional framework, this study reveals its structural contradictions. Through international comparison, it proposes optimization plans: cognitive reconstruction driven by hierarchical education and brand activities at the spiritual level; solving implementation dilemmas through dynamic management and quantitative incentives at the institutional level; strengthening team mutual discipline through safety partner systems and practical drills at the behavioral level; and upgrading guarantee capabilities through intelligent transformation and resource sharing at the material level. The study emphasizes integrating safety culture into the entire process of scientific research and teaching, and building a safety culture ecosystem with Chinese characteristics through four-dimensional collaboration. Future research can focus on the integration of digital technology and safety culture, explore differentiated paths for universities, and contribute Chinese wisdom to global safety governance.

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