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# Two Decades of Digital Transformation in Laboratory Chemical Safety: A Scientometric-Supported Systematic Review

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**ABSTRACT**

Digital technologies are steadily reshaping laboratory chemical safety, yet research in this area remains scattered across different specialties. To bring clarity to this fragmented landscape, this study adopted a hybrid approach combining scientometric mapping with a systematic literature review (SLR). Records were retrieved from Scopus and Web of Science. Scientometric techniques were used to trace publication trends, identify key journals, and visualise thematic keyword clusters, while the systematic review examined the methods, digital tools, and safety outcomes reported in each study. The findings highlight three main directions in recent digital innovation. Smart monitoring tools, especially those integrating computer vision and IoT sensors are gaining traction for improving hazard detection and situational awareness. Digital platforms for chemical information management, such as laboratory information systems, chemical hazard databases, and digitised SDS access, strengthen traceability and support more informed and coordinated decision-making. Meanwhile, virtual reality has emerged as a promising approach for enhancing safety training and competency development. Collectively, these tools illustrate how digitalisation is gradually shifting laboratory chemical safety toward more proactive, coordinated, and data-driven practices. Rather than proposing a standalone solution, this review synthesises the current evidence into a conceptual roadmap that highlights how digital monitoring, information systems, and training technologies can be combined to support integrated laboratory safety management and guide future development.

## 1. Introduction

Laboratory environments are central to scientific discovery, yet they remain places where chemical hazards must be managed with care. Whether in universities, research institutes, healthcare facilities, or industrial settings, the safe handling of chemicals underpins the quality of research and the protection of people working with them. Traditionally, chemical safety in laboratories has relied heavily on manual practices such as paper-based inventory logs, physical inspections, standard

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training sessions, and routine procedural checks. While these practices remain important, they often struggle to keep pace with growing laboratory complexity and the increasing variety of chemicals handled today [1].

In recent years, laboratories around the world have begun to adopt digital tools to enhance chemical safety management [2,3]. Technologies such as virtual reality for safety training, real-time monitoring using sensors and computer vision, and web-based information systems for chemical inventories represent promising steps toward more proactive safety practices [4]. These innovations have the potential to improve traceability, provide faster access to hazard information, and support earlier detection of unsafe conditions [5,6]. Despite this progress, research on digital solutions for laboratory chemical safety is dispersed across several fields, including chemical engineering, occupational safety, computer science, and environmental health [7,8]. As a result, it is difficult to obtain a clear picture of how digitalisation is taking place, what tools are being developed, and where gaps remain.

Despite the growth of digital tools, prior studies remain fragmented in three ways: (i) most focus on individual technologies without explaining how they fit into a broader safety system, (ii) laboratory types and safety domains (monitoring, information management, training) are studied in isolation, and (iii) there is limited synthesis explaining how these digital tools collectively improve chemical safety performance. This review directly addresses these gaps by integrating scientometric mapping with systematic evidence analysis to clarify how digital tools have evolved, where technological and organisational gaps persist, and what conceptual structure connects these innovations. In doing so, this study provides the first consolidated model of how digital monitoring, information systems, and training technologies interact within a laboratory chemical safety ecosystem.

## 2. Methodology

This study adopted a hybrid methodology that integrates scientometric analysis with a SLR. This combined approach was chosen to provide both a broad overview of publishing activity in the area of digital laboratory chemical safety and a deeper understanding of the research contributions within individual studies. The methodology consisted of three major phases: data retrieval, scientometric mapping, and systematic screening.

### *2.1 Data Retrieval and Search Strategy*

The literature search was carried out using Scopus and the Web of Science Core Collection, both internationally recognised databases known for their extensive coverage of peer-reviewed scientific publications. These databases were selected to ensure that the search captured high-quality studies from diverse disciplines including computer science, chemical safety, engineering, and laboratory management. The search was conducted in January 2025. To guide the retrieval process, a structured set of keywords was developed based on three conceptual domains central to this review:

(i) digital tools and technologies,
(ii) chemical safety, and
(iii) laboratory environments.

These domains were translated into an expanded Boolean search string designed to be inclusive enough to capture multidisciplinary work yet targeted enough to maintain relevance. The final search string applied across both databases was:

*(“digital system” OR “digital technology” OR “software” OR “database” OR “ICT” OR “information technology” OR “electronic system” OR “automation” OR “digital management” OR “digital tool” OR “information system*” OR “LIMS” OR “chemical inventory system” OR “e-SDS” OR “smart sensor*” OR “IoT” OR “digital monitoring”) AND (“chemical safety” OR “chemical hazard*” OR “chemical exposure” OR “chemical risk” OR “chemical management” OR “SDS” OR “chemical toxicity” OR “CHRA”) AND (“laboratory safety” OR “lab safety” OR “chemical laboratory” OR “research laboratory” OR “laboratory incident*” OR “lab management”).

This search strategy successfully generated a broad yet relevant dataset. A total of 53 records were retrieved (Fig 1): 24 from Scopus and 29 from Web of Science, which were then exported for preprocessing and screening.

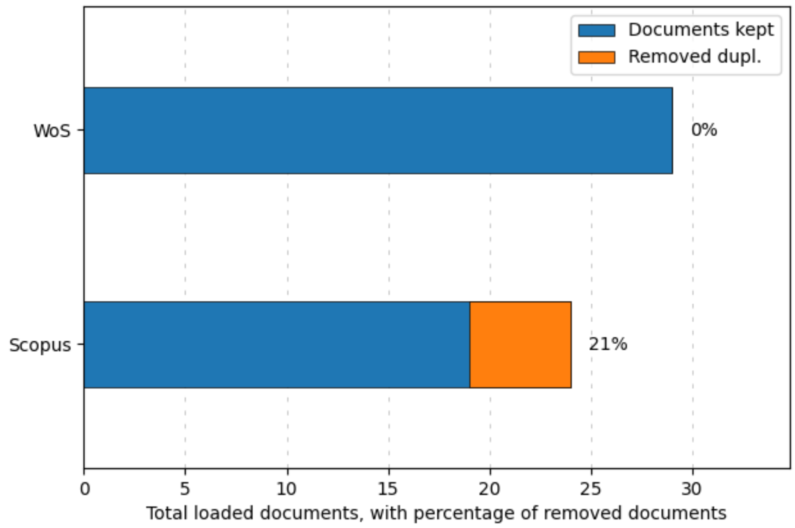


**Fig. 1.** Documents retained and duplicates removed from Scopus and Web of Science during pre-processing

### *2.2 Scientometric Pre-processing and Mapping*

Before synthesis, both datasets were merged and processed using Scientopy, which automatically removes duplicates, standardises author and keyword fields, and prepares the dataset for scientometric analysis. After de-duplication, 48 unique records remained. Scientometric mapping was then conducted to identify publication trends, keyword evolution, and thematic clusters over the last two decades. VOSviewer was used to generate co-occurrence maps and to visualise emerging research directions, especially in areas involving AI-based monitoring, digital chemical management, and virtual safety training tools. The scientometric stage provided the “macro-level” context of how digital transformation has developed within laboratory chemical safety research.

### *2.3 Systematic Screening and Eligibility Criteria*

Following the scientometric overview, the same dataset was screened systematically using predefined inclusion and exclusion criteria. Only original empirical research, published in English, focusing on laboratory safety or chemical management, and involving or informing digital tools, were considered eligible. The review includes studies from university, research, and healthcare laboratories, as these settings represent the majority of chemical-handling environments reported in the literature. Industrial chemical plants were excluded because their safety systems differ substantially from laboratory workflows. Review papers, conference proceedings, non-laboratory studies, and purely biological or environmental toxicology papers were excluded. A structured PRISMA 2020 process was applied [9]. Of the 48 records screened, 38 were excluded for not meeting eligibility requirements, leaving 10 empirical studies for full analysis.

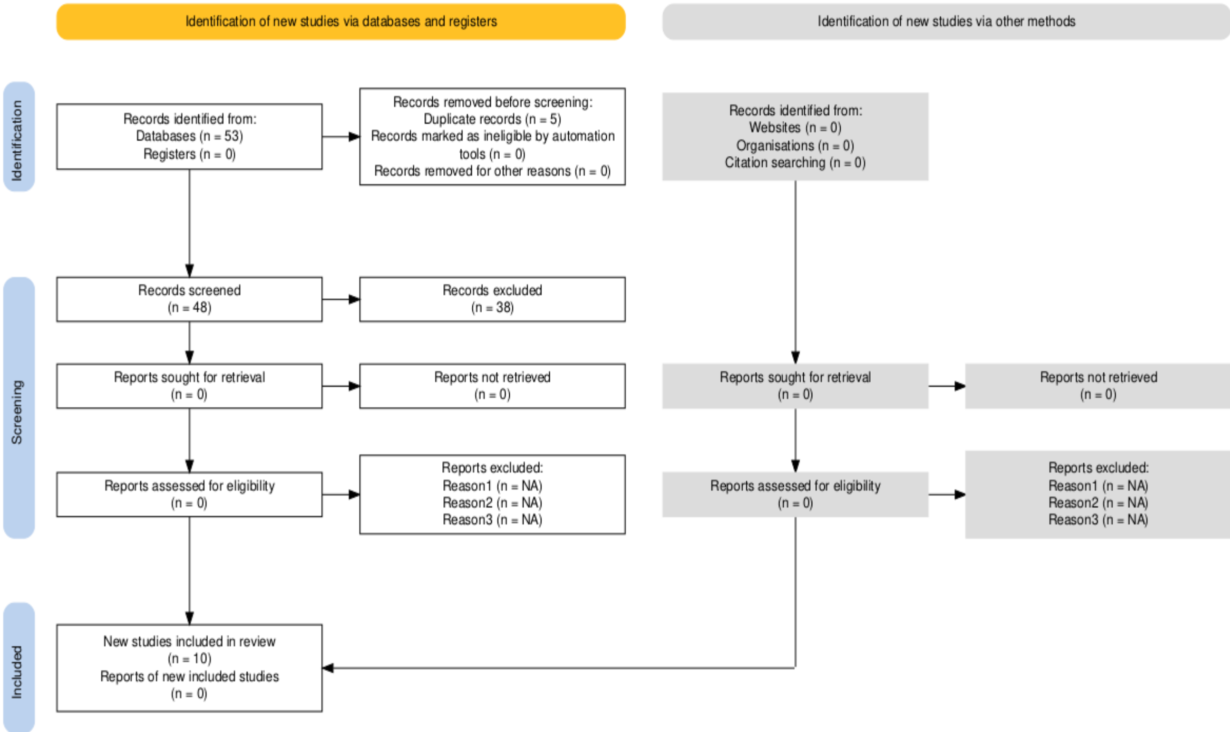


**Fig. 2.** PRISMA 2020 flow diagram showing the screening process from 53 identified records to the final 10 studies included in the systematic review.

### *2.4 Data Extraction and Synthesis*

Each of the 10 included studies was reviewed in detail. A data extraction table was developed to capture key elements such as research aims, laboratory setting, type of digital tool, methodological approach, safety outcomes, and contributions to laboratory chemical safety. The final synthesis combined scientometric findings (macro-patterns) with thematic SLR insights (micro-level contributions), enabling a rich and integrated understanding of digitalisation in laboratory chemical safety.

## **3. Results**

### *3.1 Scientometric Findings*

The scientometric analysis was conducted on the 48 unique records obtained after duplicate removal, offering a broad view of how research on digital tools for laboratory chemical safety has evolved over the past two decades. Although the primary focus of this study is the in-depth SLR of 10 selected papers, the scientometric overview helps contextualise the field's development, major publication outlets, and emerging conceptual directions.

### *3.1.1 Publication Trend (2005–2025)*

The publication trend in Figure 3 shows that research activity in this area was relatively sparse between 2005 and 2015, with only isolated contributions appearing in both databases. A noticeable upward shift begins after 2018, followed by a sharper rise between 2021 and 2025. This pattern suggests a growing recognition of the role of digital tools—such as computer vision systems, virtual safety training platforms, and chemical information management systems—in improving chemical safety and laboratory operations. The recent increase, particularly in Scopus-indexed publications, also indicates expanding interest across multidisciplinary domains including engineering, analytical sciences, and technology-oriented safety research.

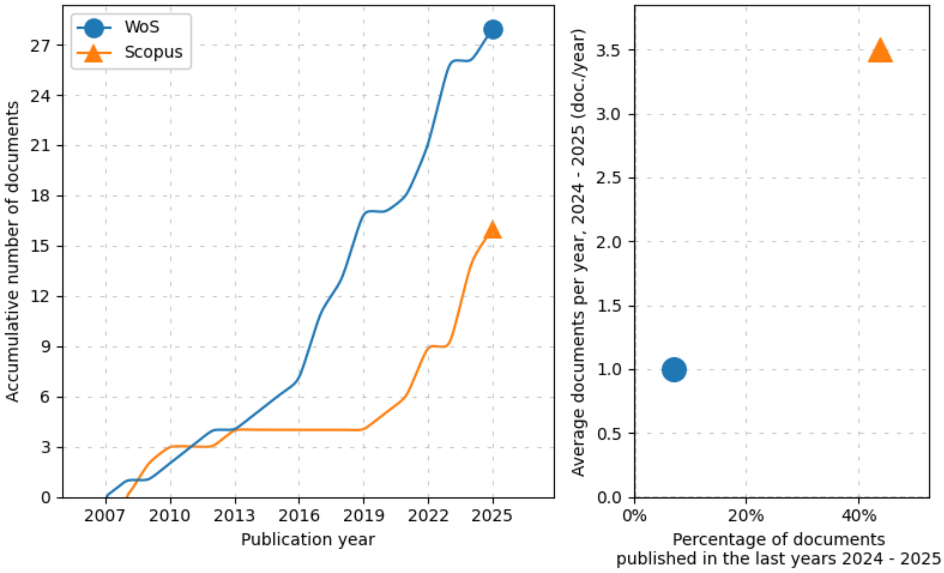


**Fig. 3.** Publication trend from Web of Science and Scopus (2005–2025), showing increased research activity in recent years.

### *3.1.2 Journal Distribution*

Figure 4 presents the distribution of journal sources contributing to this research area. *ACS Chemical Health and Safety* emerged as the most productive outlet, with over half of its contributions published in the last two years, reflecting strong contemporary engagement with digital safety topics. Other journals, including *Toxicology and Applied Pharmacology*, *Green Analytical Chemistry*, *Immunopharmacology and Immunotoxicology*, and the *Journal of Loss Prevention in the Process Industries*—also contributed relevant publications, although at lower frequencies. The diversity of journals suggests that digital laboratory chemical safety intersects multiple disciplines, from occupational exposure and toxicology to chemical process safety and analytical method development.

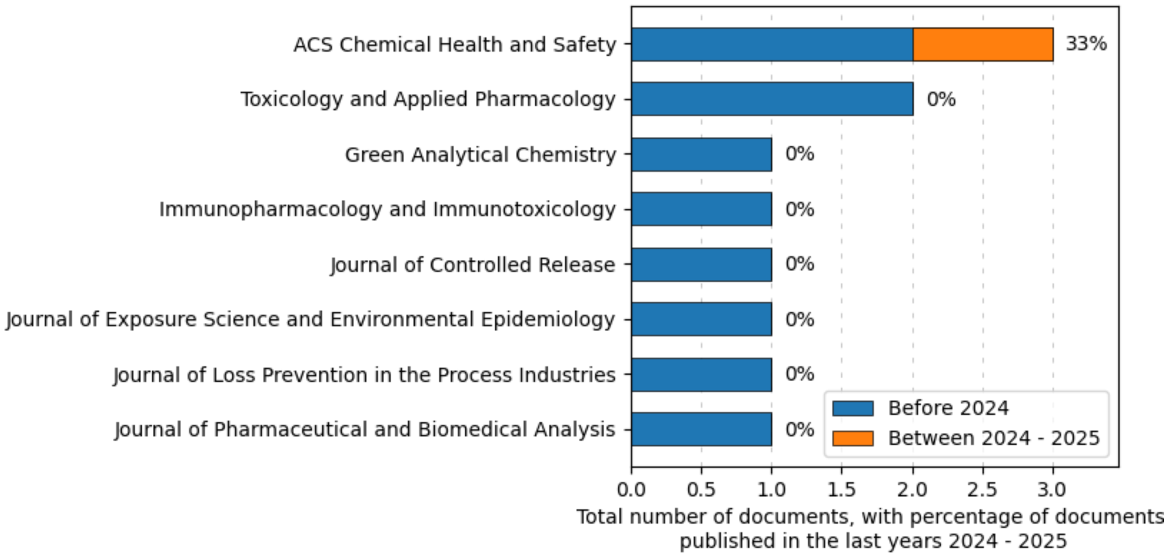


**Fig. 4.** Journal distribution of publications related to digital laboratory chemical safety, with recent contributions highlighted for 2024–2025.

### *3.1.3 Keyword Co-occurrence Clusters*

The VOSviewer keyword map (Figure 5) reveals three distinct thematic clusters that align closely with the core themes of this review. The first cluster centres on chemical safety, chemical security, and chemical risk management, highlighting foundational concerns in laboratory safety practice. The second cluster connects chemical laboratory with information management systems and web-based platforms, reflecting the rise of digital tools supporting chemical inventory tracking, SDS access, and laboratory management. A third cluster links virtual reality to safety-related terms, signalling growing interest in immersive, technology-enhanced training methods. Collectively, these clusters illustrate how digitalisation is gradually reshaping the landscape of laboratory chemical safety through both operational systems and training innovations.

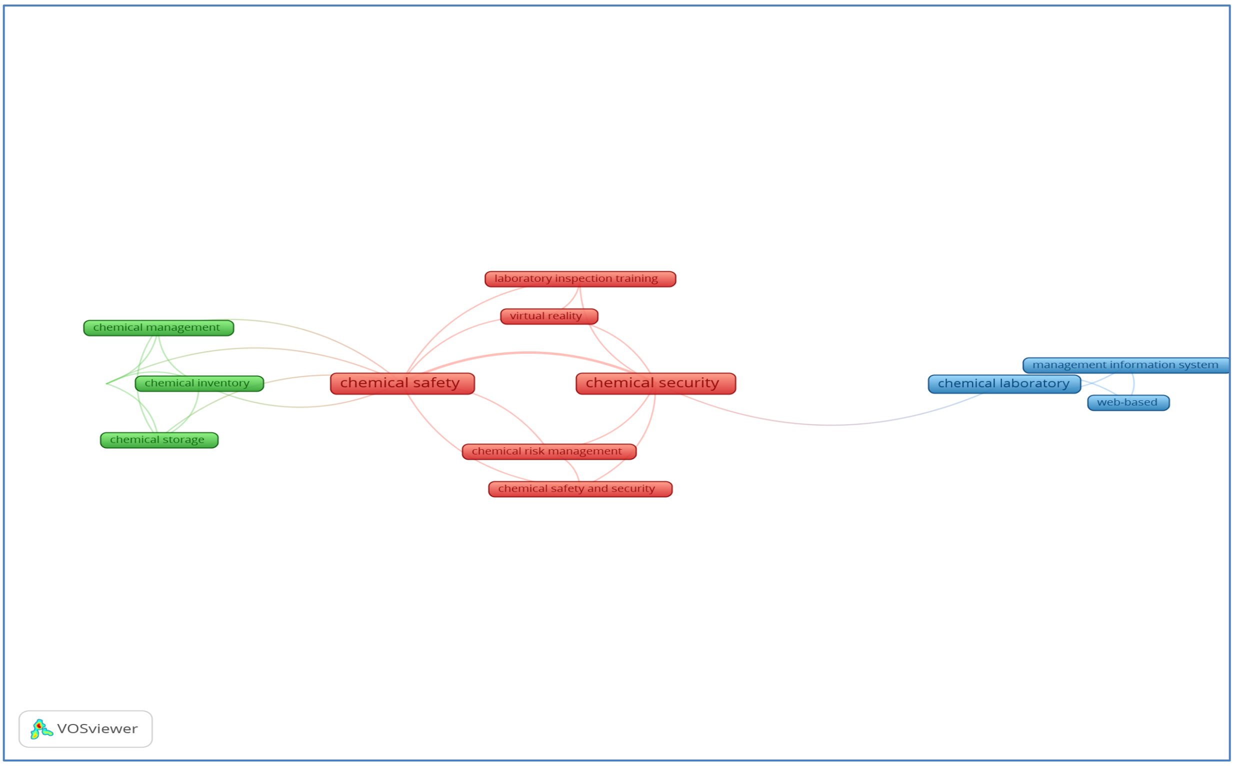


**Fig. 5.** Keyword co-occurrence map showing three main clusters

### *3.2 Systematic Review Findings*

The systematic review synthesised the key insights from 10 empirical studies that examine digital tools, technological applications, and safety practices in chemical laboratory environments. Although the studies originate from different regions and laboratory settings including universities, research laboratories, and healthcare facilities, they collectively highlight how digitalisation is advancing chemical safety in diverse ways. Three major themes emerged from the analysis: (1) smart monitoring and real-time detection systems, (2) digital chemical information and management platforms, and (3) safety culture, management practices, and training innovations. A summary of the characteristics and key findings of the ten studies is presented in Table 1.

**Table 1**
Summary of the 10 studies included in the systematic review

| No. | Study Title | Laboratory Context | Digital Tool / Focus | Methodology | Key Findings & Contribution to Chemical Safety |
|---|---|---|---|---|---|
| **1** | YOLOv5-Based Real-Time Monitoring System [10] | Educational chemistry labs | Computer vision (YOLOv5), AI hazard detection | System development + experiment | Improves real-time hazard detection and reduces need for manual monitoring. |
| **2** | VR for Laboratory Safety and Security Inspection Training [11] | University labs | Virtual reality (VR) training | Experimental evaluation | Enhances hazard recognition, engagement, and inspection competency. |
| **3** | ChlorTox Base – Chemical Hazard & Greenness Database [12] | Chemical reagent selection | Chemical hazard database; digital SDS | System design + demonstration | Integrates hazard & greenness info; improves safer chemical choices. |
| **4** | Web-Based Management Information System for Chemical Laboratory [13] | Research laboratories | Web-based MIS; digital inventory | System development | Improves traceability, reduces errors, streamlines documentation. |
| **5** | Computational Toxicology (EPA High-Throughput System) [14] | Toxicity screening labs | Predictive toxicology; high-throughput modelling | System description | Supports chemical hazard prediction and early screening. |
| **6** | Laboratory Chemical Safety Management in Chinese Universities [15] | University chemistry labs | Safety management practices (non-digital) | Case study | Identifies storage & training gaps; highlights opportunities for digitalisation. |
| **7** | Safety Supervision Levels for Hazardous Chemicals in University Labs [16] | Academic labs | Supervision model (non-digital) | Policy/management analysis | Shows increasing regulatory expectations; digital tools recommended. |
| **8** | Culturing Chemical Security System in Indonesian Labs [17] | University chemical labs | Chemical security information system | Survey + analysis | Exposes weaknesses in chemical tracking and security; digital system proposed. |
| **9** | Safety Practices Among Hospital Laboratories in Oromia [18] | Hospital medical labs | Safety management assessment | Cross-sectional survey | Reveals PPE, training, and storage shortcomings; suggests digital tools for improvement. |
| **10** | Chemical Storage & Inventory Management Practices [19] | Research laboratories | Chemical inventory, storage | Observational analysis | Highlights segregation, labeling, and documentation issues; recommends digital systems. |

#### *3.2.1 Smart Monitoring and Real-Time Detection Technologies*

Several studies demonstrated how modern digital tools enhance hazard detection and situational awareness in laboratory environments. Ali et al. [10] introduced a YOLOv5-based real-time monitoring system capable of detecting unsafe behaviours and laboratory hazards with high accuracy, significantly reducing reliance on manual supervision. Complementing this, Ameen and Samaan [13] introduced a web-based laboratory management system that includes digital monitoring functions such as inventory tracking and automated notifications. Although less advanced than AI-based detection, their findings show that even basic digital alerts can improve responsiveness and strengthen documentation accuracy. Together, these studies illustrate how emerging digital monitoring tools, ranging from machine vision models to automated MIS alerts can increase situational awareness and shift laboratory chemical safety toward more proactive detection

#### *3.2.2 Digital Platforms for Chemical Information, Inventory, and Hazard Communication*

Digital chemical information systems were among the most frequently studied designs in the dataset. Nowak, Bis, and Zima [12] introduced ChlorTox Base, a digital chemical hazard and greenness database that consolidates SDS information, hazard classifications, and environmental impact scores. Their study demonstrates how structured digital repositories support safer reagent selection and more transparent hazard communication. In parallel, Ameen and Samaan [13] developed a web-based laboratory MIS capable of managing chemical inventories and SDS access, significantly reducing errors common in manual record-keeping. Kavlock and Dix [14] expanded this perspective by demonstrating how predictive computational toxicology systems can support early chemical hazard screening, offering additional layers of risk prediction. Finally, Kuzmina et al. [19] identified weaknesses in chemical storage documentation and emphasised the need for digital inventory and traceability systems, reinforcing the operational importance of digital information tools. Collectively, these studies show that digital chemical information systems, including LIMS, SDS platforms, and hazard databases directly improve accuracy, accessibility, and compliance in laboratory chemical management.

#### *3.2.3 Laboratory Safety Practices, Culture, and Technology-Enhanced Training*

The importance of organisational and cultural factors was emphasised across several non-digital studies. Li et al. (2025) found substantial gaps in chemical storage, supervisory oversight, and training practices across Chinese university laboratories. Similarly, Mugivhisa, Baloyi, and Oluwule Olowoyo (2021) reported inconsistent adherence to hazardous chemical supervision procedures in academic laboratories. Pusfitasari [17] documented weaknesses in chemical security tracking within Indonesian laboratories and proposed digital security systems as a remedy. Sewunet et al. [18] examined hospital laboratories in Ethiopia and highlighted deficiencies in PPE use, safety documentation, and chemical handling, again pointing to the need for modernised digital tools to support compliance. Technology-enhanced training was evaluated by Ng et al. [11], who demonstrated that virtual-reality (VR) simulations increase hazard recognition accuracy and inspection competency in university laboratory settings. Their findings show the potential of VR to support competency development in environments where traditional training is insufficient.

### *3.2.4 Cross-Cutting Insights from the Ten Studies*

Across all ten studies, several cross-cutting insights emerged. First, digitalisation is accelerating but adoption varies widely: some laboratories implement advanced AI surveillance systems, while others still rely on manual recordkeeping. Second, digital tools consistently improve traceability, data accessibility, and training quality, yet interoperability between different digital systems remains a common limitation. Third, the gap between technology availability and user readiness suggests that digital transformation must be accompanied by training, policy updates, and cultural reinforcement.

Overall, the SLR demonstrates that digital tools, ranging from monitoring systems and chemical information platforms to VR training modules, offer practical and impactful pathways to enhance laboratory chemical safety. However, sustained improvement requires investment not only in technology but also in organisational commitment, usability design, and user competency.

## 4. Discussion

This review provides a consolidated understanding of how digitalisation is influencing laboratory chemical safety, drawing together both scientometric patterns and SLR evidence from ten empirical studies. The findings reveal clear signs of progress, but also highlight uneven adoption, fragmented development, and persistent organisational barriers that must be addressed to achieve meaningful digital transformation. To synthesise these insights, Fig. 6 presents a hybrid digital ecosystem model that integrates safety culture, digital information systems, and smart monitoring technologies into a cohesive laboratory chemical safety framework. The conceptual contribution of this review lies in synthesising disparate technologies into a coherent digital ecosystem model (Fig. 6). Rather than listing tools independently, the model proposes how digital monitoring, information systems, and human–organisational factors interact as interdependent subsystems. This integration provides a theoretical lens for understanding digital transformation in laboratory chemical safety—something not articulated in previous work.

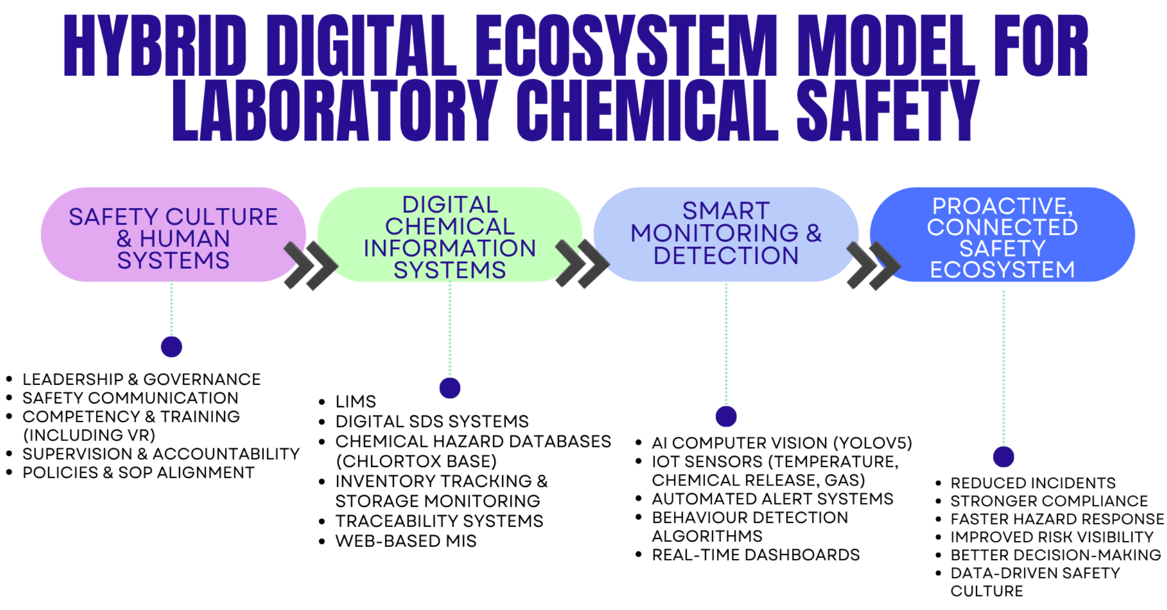


**Fig. 6.** Hybrid digital ecosystem model illustrating the relationship between safety culture, digital information systems, and smart monitoring technologies that together support a proactive and connected laboratory chemical safety system.

### *4.1 Growing Research Momentum and Fragmented Development*

The scientometric results show a noticeable surge in publications after 2018, reflecting the broader global trend of integrating digital tools such as AI-driven monitoring, digital SDS platforms, and VR-based training, into laboratory environments. This rise in digital safety technologies parallels trends observed in process safety, industrial automation, and occupational health, where digital tools are becoming increasingly embedded in routine monitoring and decision-making [20,21,5,6].

However, the SLR findings suggest that the uptake of digitalisation across laboratories remains uneven. While some studies demonstrate advanced prototypes such as YOLOv5-based hazard detection or VR inspection simulations, others report traditional challenges such as poor chemical storage practices, inconsistent PPE use, and limited safety training. This mismatch indicates that technological innovation is progressing faster than its adoption, with many laboratories still operating under conventional safety models. This gap mirrors observations in previous OSH digitalisation literature, where tools may exist, but readiness, infrastructure, and resources limit their effective implementation. Synthesising these technologies is important because laboratories often adopt digital tools in isolation, leading to duplicated work and inconsistent safety performance. A unified understanding helps researchers prioritise innovation areas, guides laboratory managers in selecting complementary tools rather than standalone applications, and assists regulators in identifying digital capabilities that can strengthen compliance and oversight.

### *4.2 Evaluation of Emerging Digital Tools and Approaches*

#### *4.2.1 AI and Smart Monitoring Systems*

Firstly, AI-based monitoring systems show strong potential in improving hazard detection, especially for identifying unsafe behaviours, an area where human supervision is inconsistent. These findings align with broader trends in machine-vision applications for safety, where computer vision reduces observer fatigue and enhances situational awareness [20,21]. However, most systems identified in this review remain early-stage prototypes, tested in controlled environments rather than operational laboratories. This limitation reflects a well-documented challenge in safety innovation where promising technologies often struggle to transition from pilot testing to real-world deployment due to variability in lighting, behaviour, workflow, and laboratory layout.

#### *4.2.2 Digital Chemical Information Platforms*

Building on the need for reliable hazard detection, chemical hazard databases, and LIMS platforms consistently improve access to accurate information and strengthen traceability. These findings echo recent efforts in chemical management globally, where digital inventories help reduce human error and strengthen regulatory compliance [22,23,24]. Nevertheless, several reviewed studies highlight that laboratories, especially in universities or low-resource settings, still rely heavily on manual records. This gap therefore reinforces the need for affordable, interoperable systems and institutional commitment to long-term digital adoption.

#### *4.2.3 Training and Competency Enhancement Technologies*

In parallel with digital information systems, VR-based safety training is gaining momentum as an alternative to conventional classroom-based instruction. Its benefits such as immersion, realism, and controlled exposure to hazardous scenarios are consistent with training innovations reported in industrial and emergency response settings [25,26]. However, very few studies measure long-term learning retention, behavioural transfer, or cost–benefit justification. As a result, VR remains an important but underutilised opportunity for modernising laboratory safety training.

### *4.3 Persistent Operational and Cultural Barriers*

Despite these technological advancements, a critical insight from this review is that many laboratories still struggle with basic safety practices regardless of technological availability. Weak chemical storage, inconsistent PPE compliance, unclear safety communication, and poor supervisory oversight appeared repeatedly across studies, from hospitals to university laboratories. Taken together, these recurring issues reflect deeply rooted cultural and organisational factors that digital tools alone cannot resolve. Moreover, the broader safety literature consistently shows that technology is most effective when embedded within a strong safety climate, competent leadership, and clear institutional governance. In laboratories where safety responsibilities are poorly defined or training is irregular, digital tools risk becoming underused add-ons rather than meaningful contributors to risk reduction. Ultimately, the success of digitalisation depends not only on the tools themselves but on organisational readiness, user trust, and the ability to integrate technology into daily practice.

### *4.4 Need for Integration and Interoperability*

Finally, one of the most striking findings is the fragmented nature of digital safety tools. Most reviewed systems operate independently, monitoring systems detect behaviours, databases store chemical information, LIMS track inventories, and VR improves training, but very few examples demonstrate integrated platforms. This lack of connected architecture limits efficiency, creates duplicate work, and reduces the likelihood of widespread adoption. Current best practices in digital transformation emphasise interoperability and the creation of connected safety ecosystems. For instance, linking incident detection with inventory records or connecting chemical databases to real-time monitoring logs can significantly enhance decision-making and response time. The absence of such integrated systems across reviewed studies suggests that laboratory digitalisation remains in an early developmental stage, lacking the cohesive frameworks commonly observed in Industry 4.0 environments or advanced process safety systems. Future research should move beyond prototype development toward real-laboratory implementation studies that measure incident reduction, response time improvements, and user competency gains. There is also a need for interoperable frameworks that connect monitoring data, chemical inventory systems, and training records into a unified platform. Methodologically, longitudinal studies and mixed-methods evaluations will be essential to determine the sustained impact of digital tools on safety culture and compliance.

## 5. Limitation

This review is limited by the small number of empirical studies currently available, reflecting the early stage of digitalisation in laboratory chemical safety. Only peer-reviewed English-language publications were included, which may exclude relevant regional or technical reports. The scientometric analysis was based on author-provided keywords, which may vary in consistency. Finally, because several digital tools remain in prototype stages, long-term effectiveness and real-world validation are still limited in the available evidence.

## 6. Conclusion

This review set out to consolidate current knowledge on digital tools supporting laboratory chemical safety by combining scientometric analysis with a systematic review of ten empirical studies. The findings confirm that three categories of digital innovations: smart monitoring systems, digital chemical information platforms, and technology-enhanced safety training, are the most prominent developments in this domain. Smart monitoring tools, particularly AI-based vision systems and IoT sensors, improve real-time hazard detection. Digital information platforms strengthen chemical traceability and streamline SDS access, while virtual reality enhances user competency through immersive training. These results directly address the research objective by demonstrating that digitalisation is gradually shifting laboratory chemical safety toward more proactive, data-driven, and system-supported practices that enable earlier hazard detection, faster access to chemical risk information, improved traceability of chemical movement, and more consistent safety competency development. However, gaps remain in system interoperability, adoption readiness, and integration across laboratory workflows. Future studies should focus on validating digital tools in real laboratory settings, developing unified digital safety frameworks, and assessing long-term impacts on incident reduction, compliance, and safety culture.

### Acknowledgement
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