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Systematic Review

Trends and Future Directions in Mitigating Silica Exposure in Construction: A Systematic Review

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Abstract

Respirable crystalline silica is a well-established occupational hazard in construction work. Despite increased awareness, consistent exposure control remains a challenge, particularly in dynamic and resource-constrained environments. Respirable crystalline silica exposure in construction environments challenges the achievement of the United Nations Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-Being) and SDG 8 (Decent Work and Economic Growth). Respirable crystalline silica particles cause severe health complications, including silicosis, lung cancer, cardiovascular diseases, and autoimmune disorders, representing a significant barrier to achieving SDG 3.9's target of reducing deaths and illnesses from hazardous chemical exposures by 2030. This systematic review evaluates two decades of advancements (2004–2024) in respirable crystalline silica identification, characterisation, and mitigation within construction, synthesising evidence from 143 studies to assess progress toward sustainable occupational health management. This review documents a paradigmatic shift from traditional exposure assessment toward sophisticated monitoring approaches incorporating real-time detection systems, virtual reality–Computational Fluid Dynamics simulations, and wearable sensor technologies. Engineering controls, including local exhaust ventilation, wet suppression methods, and modified tool designs, have achieved exposure reductions exceeding 90%, directly supporting SDG 8.8's commitment to safe working environments for all workers, including migrants and those in precarious employment. However, substantial barriers persist, including prohibitive costs, inadequate infrastructure, and regional regulatory disparities that particularly disadvantage lower-resourced countries, contradicting the Sustainable Development Goals' principles of leaving no one behind. The findings advocate holistic approaches integrating technological innovation with context-specific regulations, enhanced international cooperation, and culturally adapted worker education to achieve equitable occupational health protection supporting multiple Sustainable Development Goals' objectives by 2030 and also highlighting potential areas for future research.

Keywords: respirable crystalline silica; construction workers; exposure assessment; engineering controls; occupational health regulations; real-time monitoring; silica dust mitigation

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1. Introduction

Occupational exposure to respirable crystalline silica (RCS) continues to pose significant environmental and public health hazards globally, especially in the construction industry. Recognised as a hazardous material due to its severe long-term respiratory and cardiovascular health impacts [1,2], RCS remains a critical challenge requiring effective management through innovative and contextually appropriate control measures [3–5]. Over the past two decades, there has been considerable advancement in methodologies for identifying and monitoring silica exposure in occupational environments. Technological developments, particularly in real-time monitoring and analytical techniques, have significantly enhanced the precision of exposure assessment and the effectiveness of silica dust control measures [6,7]. Recent studies highlight the evolution of exposure assessment methodologies, shifting from basic, static measurements toward advanced real-time monitoring approaches integrating wearable technology, sensors, and predictive analytics [8–10].

The characterisation of silica dust exposure has expanded beyond traditional respiratory measures, incorporating a more comprehensive understanding of long-term health implications, such as cardiovascular diseases and autoimmune conditions linked to silica inhalation [11]. These developments illustrate the importance of adopting broader health surveillance strategies to effectively capture the impacts of silica exposure [11,12]. Technological innovations have also transformed mitigation strategies, enabling proactive risk management through real-time monitoring, engineering controls, like local exhaust ventilation (LEV), wet methods, and integrated tool modifications [13–15]. Despite these advancements, regional disparities in regulatory frameworks, enforcement capabilities, and infrastructure availability significantly influence the practical effectiveness of these control strategies [5,16,17].

This research directly contributes to achieving several United Nations Sustainable Development Goals [18] through specific, quantifiable mechanisms that extend beyond the 2030 Agenda. The focus on mitigating occupational silica exposure demonstrates strong alignment with SDG 3 (Good Health and Well-Being), particularly Target 3.9, by addressing hazardous chemical exposure that affects an estimated 23 million workers worldwide in high-risk occupations [19,20]. Evidence shows that effective silica control measures can prevent approximately 15,000 annual deaths from silicosis globally. Advanced monitoring technologies can reduce exposure levels by 60–80% compared to baseline measurements, while comprehensive control strategies may lower silica-related lung cancer incidence by 30–50% over a 20-year period [18]. Economic modelling indicates that every USD 1 invested in advanced silica control technologies yields USD 3–7 in reduced healthcare costs and productivity losses, with potential global savings exceeding USD 2.4 billion annually. These measurable outcomes provide clear pathways toward achieving Target 3.9's goal of substantially reducing deaths and illnesses from hazardous chemicals [21].

The research also supports SDG 8 (Decent Work and Economic Growth), particularly Target 8.8, by delivering measurable workplace safety improvements and economic benefits [18]. Real-time silica monitoring systems can reduce work-related absences by 25–40% through early intervention, equating to approximately 2.1 million additional productive workdays annually in the construction sector. Advanced control technologies can lower compliance costs by 35–50%, generating estimated savings of USD 850 million annually across OECD countries [22]. Enhanced safety measures are associated with 20–30% improvements in worker retention rates, with particularly significant benefits for migrant and temporary workers, who face up to 40% higher silica exposure risks than permanent employees. These outcomes directly support the protection of vulnerable worker populations and the promotion of safe working environments [23–25]. Furthermore, by reducing airborne dust in urban construction environments, the research advances SDG 11 (Sustainable Cities and Communities), primarily through improved air quality and reduced health risks to surrounding communities. The integration of dust control technologies, hazard mitigation strategies, and safer construction practices contributes to creating sustainable urban environments that protect both workers and residents [13–15].

This systematic review's examination of emerging technologies and integrated control measures provides a roadmap for implementing sustainable construction practices that minimise environmental and health impacts during urban development [13–15]. This alignment is particularly important as global urbanisation accelerates, requiring construction practices that balance economic development with health and environmental protection while addressing the complex challenges of maintaining safe working conditions in rapidly evolving urban construction environments [11,12]. This systematic review aims to critically analyse the existing literature on technological and regulatory developments in silica dust identification, exposure characterisation, impact assessment, and mitigation within construction settings. Specifically, the objectives of this review are as follows:

- Evaluate advancements in measurement and real-time monitoring methodologies for silica exposure in construction.
- Assess the effectiveness of existing technological controls, such as engineering interventions and PPE utilisation.
- Explore regional variations in regulatory approaches and their impact on occupational health outcomes.
- Examine strategies to enhance worker awareness, engagement, and organisational safety culture and reinforce effective control measures.
- Identify barriers to the widespread adoption of advanced silica exposure control technologies, especially in lower-resourced regions.
- Highlight critical research gaps in silica exposure measurement and control to inform future studies and policy development.

The outcomes of this systematic review hold significant practical implications for occupational health and safety management within the construction industry, with direct relevance to achieving multiple SDG targets. By synthesising current knowledge on technological advancements and regulatory practices, this review provides evidence-based guidance crucial for policymakers, industry stakeholders, and practitioners working toward the Sustainable Development Goals. The findings will inform the design and implementation of more effective control measures that support SDG 3's health objectives, strengthen worker education and safety compliance aligned with SDG 8's decent work targets, and support regulatory harmonisation efforts that contribute to SDG 11's sustainable communities. This contribution supports the interconnected nature of the SDGs, demonstrating how occupational health improvements in construction can simultaneously advance health and well-being, decent work, and sustainable community development objectives [10]. This research provides a scientific foundation for policy interventions and technological innovations that can accelerate progress toward the 2030 Agenda for Sustainable Development, particularly in addressing work-related health hazards that disproportionately affect vulnerable worker populations worldwide. Through its comprehensive analysis of silica exposure control measures, worker awareness strategies, and regulatory frameworks, this systematic review contributes to building the evidence base necessary for achieving substantial reductions in occupational health hazards, supporting the global commitment to protect workers' health and promote decent work for all.

2. Methodology

To systematically gather evidence regarding technological and regulatory advancements in the identification, characterisation of exposure, impact assessment, and mitigation of silica dust within construction environments, a comprehensive systematic literature review (SLR) was undertaken. This method is recognised as a rigorous, transparent, and reproducible approach that not only aids in the development of theoretical frameworks but also identifies emerging research domains while addressing areas saturated with existing studies [26,27]. This research was conducted in line with the recommendations outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) protocols [28].

2.1. Data Sources and Search Strategy

In this systematic literature review (SLR), information was collected by searching the electronic databases Scopus, PubMed, and Google Scholar (GS). Scopus was selected because of its broad coverage, including more peer-reviewed journals than other databases [29]. PubMed was chosen because of its comprehensive coverage of the occupational health and safety literature [30]. Furthermore, this SLR incorporated GS as one of the search databases, despite its recognised limitations for comprehensive systematic searches, to maximise the inclusivity of the literature. The inclusion of GS aligns with recent trends in SLR methodologies that advocate for a more inclusive approach to literature searching [31]. The search was limited to review papers only in GS for snowballing purposes and managing the large volume of data. This method helps identify relevant primary studies not captured in the original search string. This approach reduced the initial search results from over 16,000 to a more manageable 2240 papers, focusing on reviewable content. This strategy aligns with recommendations to refine GS searches because of its broad scope and lack of advanced filtering options [30].

The development of the search string was guided by key terms such as "crystalline silica exposure" and "Construction Safety," which encapsulate the primary focus on occupational hazards and protective measures within the construction industry. The following keyword search strategy was applied to all databases: ("silica dust" OR "Quartz Dust" OR "crystalline silica" OR "respirable silica" OR "silica exposure" OR "quartz exposure") AND ("construction" OR "building"). The outlined search strategy represents the final iteration, implemented to ensure the highest level of inclusion. This was established following a series of trial searches, during which the methodology was adjusted according to the outcomes of the papers retrieved.

2.2. Inclusion and Exclusion Criteria

During the preliminary literature search, criteria were established to ensure that only the most pertinent studies were incorporated into this review. The search was limited to English-language papers published from 2004 to the end of 2024. All database searches were conducted between 15 and 20 December 2024. A considerable number of prior studies relied on population data from previous decades, during which the exposure to RCS was markedly higher. It is important to note that exposure limits have been revised over time in response to evolving health standards [32]. Additionally, this systematic literature review included only peer-reviewed journal articles to guarantee the quality and dependability of the material [33].

This research focused on the exposure to RCS within the construction sector and its impact on construction workers. The term "construction work" refers to a range of activities related to the alteration, conversion, fitting-out, commissioning, renovation, repair, maintenance, refurbishment, demolition, decommissioning, or dismantling of a structure. It is pertinent to note that studies addressing activities outside the construction domain, including mining, mineral exploration or extraction, tunnelling, and road construction, were not considered in this analysis.

2.3. Data Extraction

The data were recorded in a Microsoft Excel worksheet. Two authors independently reviewed the titles, abstracts, and full texts, extracting all relevant data in accordance with the PRISMA 2020 guidelines. Duplicates were identified using the automatic detection function in EndNote 21, followed by manual review to ensure accuracy. Any disagreements regarding the inclusion of studies were resolved through discussions within the research team. The process of data identification, screening, and inclusion is summarised in Figure 1. Ultimately, a total of 143 studies were included in the final review.

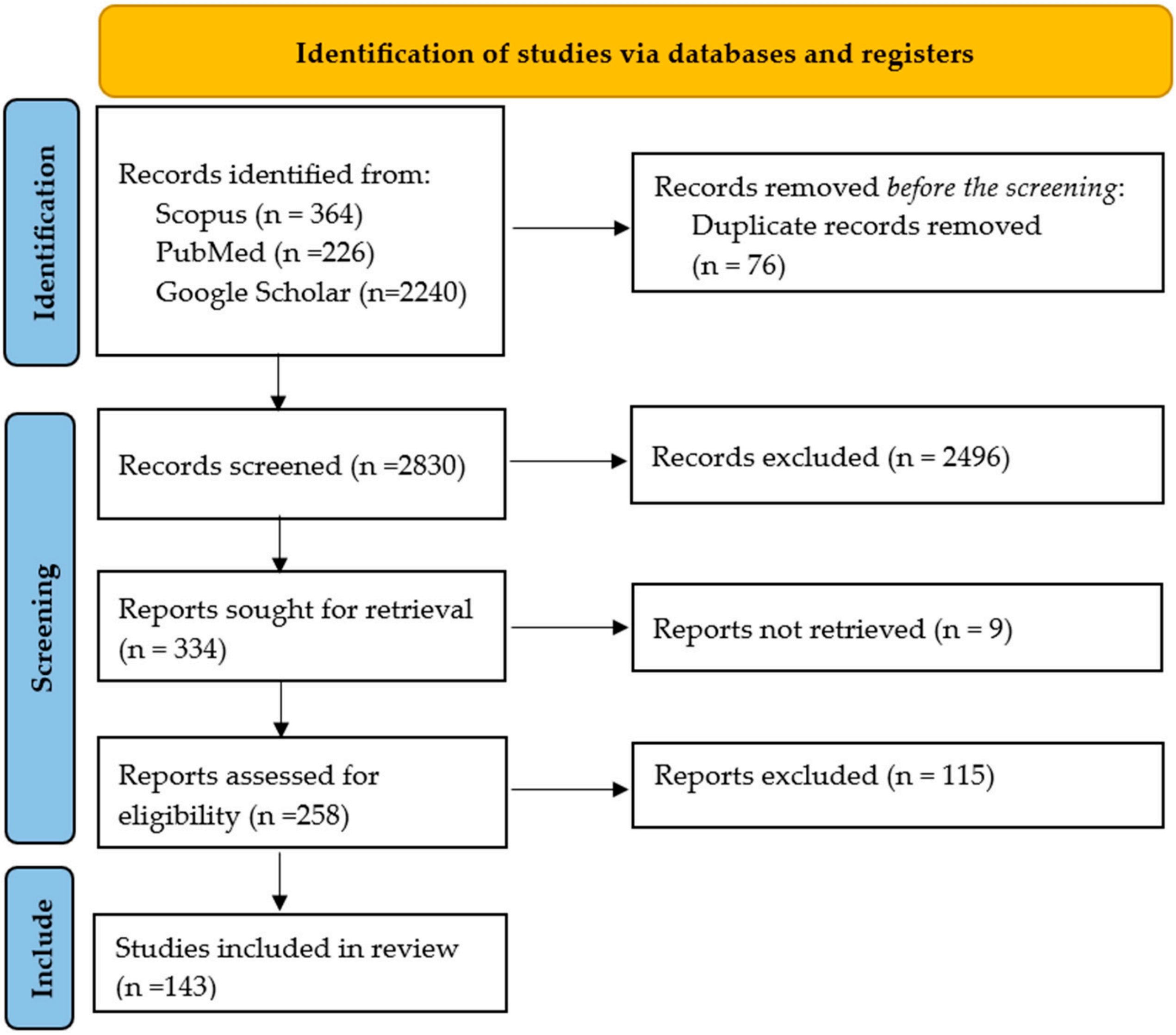

Figure 1. PRISMA 2020 flow diagram of the study selection procedure.

2.4. Data Synthesis and Presentation

The analysis and synthesis of the selected literature were conducted using qualitative methods. The general characteristics of each study are summarised in Table 1. The first part of the study presented the bibliography details from the selected papers for this SLR. VoS-Viewer and MS Excel tools were utilised to visualise the data in this section. The second part of the study was carried out to discuss the methods, new inventions, and identified trends.

Table 1. Clustering of research methodologies in silica exposure studies.

Clusters	Methodologies	Countries
Monitoring and Assessment	Exposure assessment monitoring	USA, Sweden, Australia, Hong Kong, Nepal, UK, Canada, Italy, Denmark, New Zealand, Ireland, Netherlands, South Korea, Finland, France, Slovenia, Nepal, Netherlands
	Biomonitoring study	Turkey, Egypt
	Surveillance study	Israel
	Emission factor study	USA
	Retrospective assessment	USA
Experimental and Investigative Research	Experimental evaluation	USA, USA, China, India
	Numerical and experimental investigation	USA
	Field evaluation	USA
	Process evaluation	Netherlands
	Characterisation study	USA
Epidemiological and Population Studies	Epidemiological study	Canada, China, Sweden
	Prevalence study	Australia, Nepal, Uganda
	Cohort study	Australia, Sweden
	Clinical study	Norway, France, Greece, USA
Analytical and Modelling Approaches	Statistical modelling	Canada
	Bayesian analysis	Spain
	Economic analysis	Canada
	Dose–response assessment	China
	Temporal evaluation	USA
	Comparative analysis	Australia, UK, USA, Canada
Methodology and Tool Development	Methodology development	USA, UK
	Tool development	Canada
	Checklist model development	USA
Risk and Policy Analysis	Risk assessment	Iran, Netherlands, Malaysia, Canada
	Regulatory and policy analysis	USA, India
	Industry analysis	Pakistan
Literature and Case Study Research	Literature review	USA, Australia, Greece, UK, Canada, China, Poland, South Korea, Spain, Italy, South Africa, Brazil, Ghana
	Case study	USA, Poland, Italy, UK, China, Australia
Intervention and Program Evaluation	Intervention design study	Netherlands
	Randomised control intervention	Netherlands

3. Results and Discussion

3.1. Bibliography Details

Figure 2 displays the annual distribution of publications about RCS dust research in the construction industry from 2004 to 2024. Initially, the research output was relatively low, with fewer than five papers published annually until around 2015. From 2015 onwards, there has been a gradual increase, reflecting growing academic and industry interest in silica exposure. The most notable rise begins around 2020, with publication numbers peaking in 2023, reaching 19 papers. This upward trend highlights an intensified focus on silica exposure, likely due to increased awareness of its health impacts and advancements in dust control measures in construction and related industries. Contributions come from diverse journals, highlighting interdisciplinary interest, including expansion in the scope to environmental research, public health, and occupational medicine. This distribution shows the breadth of research on silica exposure across occupational, environmental, and health disciplines.

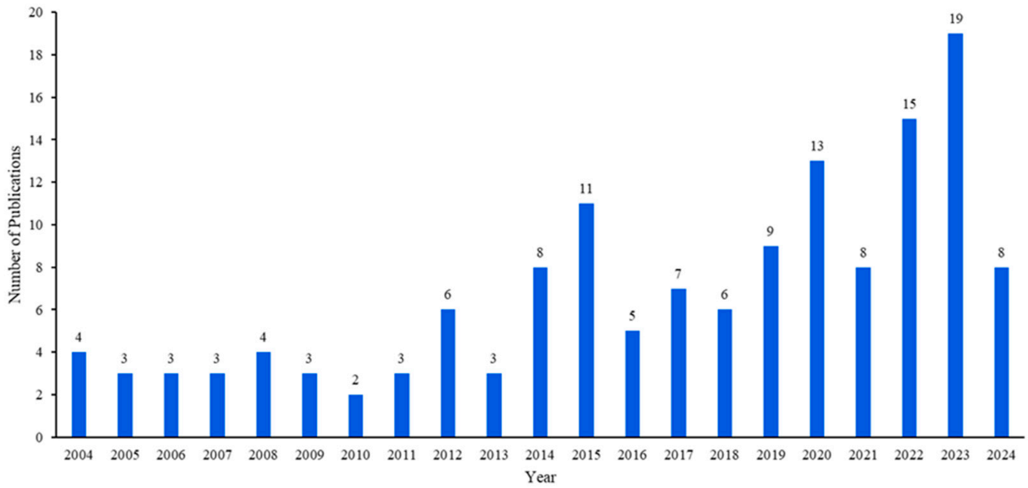

Figure 2. Annual publication trend in silica exposure research in the construction industry.

The co-author network analysis reveals a robust and evolving collaborative structure in silica exposure research, marked by distinct clusters and time-based patterns (Figure 3). Early collaborations, represented in blue, are anchored by foundational researchers like Heederik [34–40], Lavoué [6,9,41–43], Olsson [34,42,44], and Peters [42,44,45], whose long-standing contributions have shaped the field. These researchers lead dense clusters, indicating cohesive research teams focused on occupational silica exposure and health. Over time, additional authors have joined these networks, expanded the research scope, and reinforced established findings.

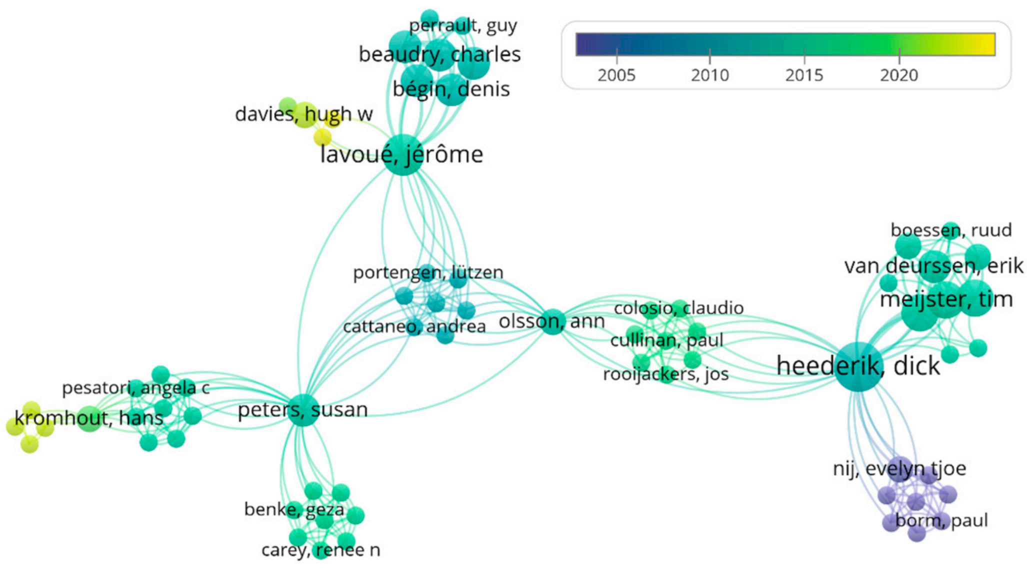

Figure 3. Co-author relationship in silica exposure research in the construction industry.

Recent collaborations, highlighted in yellow, suggest a new wave of interest, potentially driven by emerging challenges in silica exposure, technological advancements, and evolving health regulations. The research led by Gorman Ng, Li, Lavoué, and Davies [6] and Davies and Gorman-Ng [46] has emerged as particularly influential in bridging multiple disciplines within occupational health and safety. Their work integrates industrial hygiene, epidemiology, and engineering controls while incorporating insights from behavioural sciences and public health policy. This interdisciplinary approach has proven especially valuable in developing comprehensive workplace exposure assessment and control measures strategies. The collaborative research by Peters, Vermeulen, Portengen, Olsson, Kendzia, Vincent, Savary, Lavoué, Cavallo, and Cattaneo [42] and Consonni, Matteis, Pesatori, Bertazzi, Olsson, Kromhout, Peters, Vermeulen, Pesch, and Brüning [44] has facilitated valuable cross-institutional and international collaborations in silica exposure research. Their work builds upon silica exposure studies, creating impactful global connections between research institutions. This evolution from earlier research to current diverse collaborations reflects the field's dynamic growth and adaptation to emerging challenges in understanding and controlling silica exposure.

3.2. Methodologies, Geographical Scope, and Key Performance

Intending to analyse silica dust control measures, worker awareness, and safety practices within the construction industry, this study assessed the scope of methodologies, measurement techniques, and indicators in the reviewed publications. A thorough examination of both procedures and scopes of 143 articles published between 2004 and 2024 reveals significant advancements in silica exposure research. As summarised in Table 1, a global effort has been made to understand, assess, and mitigate the risks associated with RCS across the construction industry. The clustering of research methodologies reveals eight major clusters, each encompassing specific methodologies that align with distinct research purposes and approaches.

Table 1 reveals that silica exposure research has witnessed remarkable global advancements in understanding, assessing, and mitigating risks associated with RCS across various industries. Research conducted in the past two decades reveals a dynamic evolution in research approaches, geographical scope, and focus areas, underscoring the widespread nature of silica exposure concerns and the global scientific community's commitment to addressing this critical occupational health issue. It extends across multiple continents, with significant contributions from diverse regions. Researchers in some countries have conducted multi-method studies, while others have focused on specific methodologies.

The United States leads in research volume, with comprehensive studies spanning exposure assessment to regulatory frameworks [16,47,48]. European contributions have been particularly robust, with specialised focus areas in different countries: the Netherlands has emphasised workplace exposure controls [38,40], Poland has concentrated on environmental monitoring [49,50], the UK has focused on regulatory compliance [51,52], and Italy has advanced epidemiological research [53,54].

In the Pacific region, Australia has emerged as a key contributor, particularly in artificial stone-related silicosis research [55,56], with complementary studies from New Zealand focusing on occupational health surveillance [57]. Emerging economies have significantly expanded the global knowledge base, as detailed in Table 1. China has focused on exposure assessment and control technologies [4,58], while Iran has contributed valuable epidemiological studies [59,60]. India's research has emphasised workplace interventions and policy development [5,61], particularly in response to rapid urbanisation and the construction sector's growth.

There has been a notable evolution in research methodologies throughout the years. Early studies (2004–2010) primarily focused on foundational exposure assessments and the evaluation of control technologies. The middle period (2011–2017) shifted toward more sophisticated approaches, including statistical modelling, intervention studies, and complex exposure assessments. In recent years (2018–2024), the research landscape has become increasingly multifaceted. While exposure assessments remain a cornerstone of the field, there has been a marked increase in epidemiological studies examining long-term health effects, economic analyses evaluating the cost-effectiveness of interventions, and the development of practical tools for industry use. This period has also witnessed the application of cutting-edge technologies, such as 3D printing and numerical modelling, to study and mitigate silica exposure.

The construction industry has primarily focused on silica exposure research, reflecting its significant contribution to occupational health and safety. However, studies have consistently addressed other high-risk sectors, such as stone working and manufacturing. In recent years, there has been growing attention to emerging industries and practices, including artificial stone processing, green building technologies, and 3D printing in construction. This expansion in scope demonstrates the field's responsiveness to evolving industrial landscapes and new potential sources of silica exposure.

The key indicators studied have remained relatively consistent over time, with RCS levels and dust concentrations being the most frequently measured variables. However, there has been an evolution in the study of the impact of silica exposure on health. While silicosis has been a consistent focus, recent years have seen increased attention to other health effects, such as lung cancer, cardiovascular disease, and autoimmune conditions [11]. This broadening of health concerns reflects a progressive understanding of the potential impacts of silica exposure.

The research methodologies employed over this period are diverse, ranging from exposure assessments and experimental studies to literature reviews and policy analyses. This variety reflects the complex nature of silica exposure research, which requires multi-faceted approaches to address health, engineering, and policy challenges. Experimental studies have evaluated control measures, such as saw blade designs and ventilation systems [62], while epidemiological studies have investigated long-term health outcomes [11]. Researchers have also addressed unique challenges in developing nations, where the balance between economic growth and occupational health concerns presents additional complexities [63].

Despite these advancements, limited research has examined the effectiveness of mitigation strategies in small-scale or informal construction settings, predominantly in low- and middle-income countries. Longitudinal studies that link exposure levels to specific health outcomes over extended periods also remain scarce. Another critical gap lies in the integration of psychosocial and organisational factors that influence silica exposure risk. Although innovative technologies are increasingly adopted, there is a lack of evidence assessing their real-world applicability, user acceptance, and long-term sustainability across diverse work environments and cultural contexts.

Differences In Silica Exposure Across Various Regions

The control of silica dust exposure in construction varies significantly across regions due to differing exposure limits and regulatory standards. In the USA, the Occupational Safety and Health Administration (OSHA) implemented a permissible exposure limit (PEL) of 0.05 mg/m^3 for silica in construction, alongside an action limit (AL) of 0.025 mg/m^3 [16]. Similarly, Canada has adopted the American Conference of Governmental Industrial Hygienist's Threshold Limit Value (ACGIH TLV) of 0.025 mg/m^3 in seven provinces and at the federal level [6,17]. European countries like Italy and Denmark adhere to the European Directive's exposure limit of 0.1 mg/m^3, although discussions around revising this limit for added protection continue [6,53]. In contrast, most countries in the Asian region, including India, Pakistan, Nepal, and Thailand, which lack comprehensive national programmes for silicosis control, face challenges in enforcing consistent standards and coordinated action between stakeholders, which exacerbates exposure risks [5].

Cultural attitudes toward worker safety also influence the implementation and effectiveness of silica dust control. In the USA, workers generally have a high awareness of dust control methods, possibly due to consistent training and regulatory oversight [16].

However, in countries like India, there are concerns about the lack of proper medical examination or job security for workers diagnosed with silica-related illnesses, which may deter individuals from reporting health issues and further negatively impact their health [5]. In Scandinavian countries, particularly Finland, robust governmental regulations mandate health checks for workers in high-risk tasks, leading to lower overall exposure rates [64]. While robust health and safety regulations are generally in place for the construction industry in Europe, temporary worksites—which are common in construction—present unique challenges for effectively controlling silica dust, resulting in higher variability in exposure levels, especially for immigrant workers [65].

In addition, seasonal and environmental factors contribute to regional variations in silica exposure. For example, research in Canada indicates that RCS levels tend to be higher in warmer months due to increased dust generation in dry weather conditions [17]. Such seasonal variations necessitate adaptable safety practices, yet cultural differences in prioritising worker safety and equipment use can hinder the consistent implementation of these practices. For instance, while developed countries increasingly utilise primary prevention techniques, such as personal protective equipment (PPE) and environmental ventilation, compliance can vary widely in developing countries where regulatory enforcement is less stringent [63,66]. These disparities underscore the impact of regional and cultural factors on silica dust control, with both regulatory standards and societal attitudes playing pivotal roles in shaping the health outcomes for construction workers exposed to respirable silica dust. Figure 4 illustrates the diverse regulatory limits for crystalline silica exposure worldwide, measured as an 8 h time-weighted average (TWA).

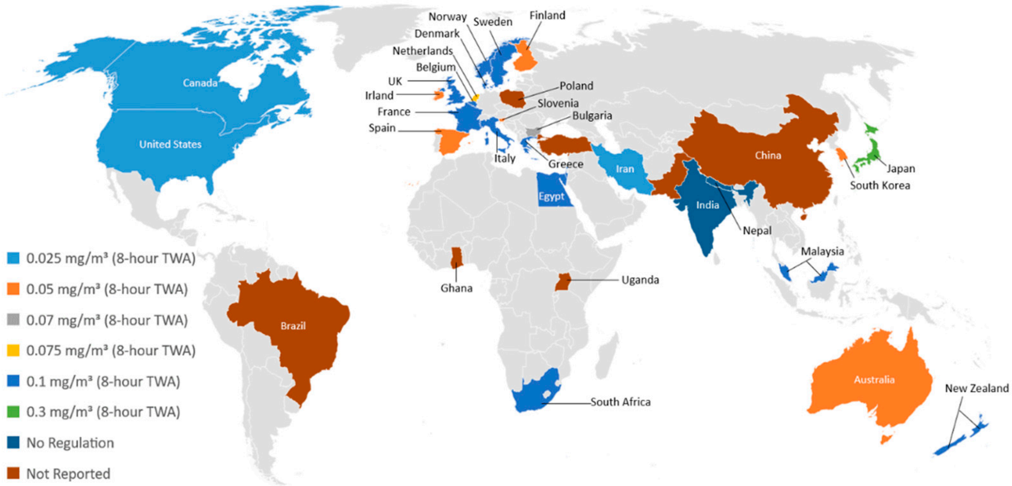

Figure 4. Time-weighted average silica exposure limits worldwide.

These differences reveal the complex interplay of regulatory, cultural, and environmental factors and highlight important gaps in the global management of silica exposure in construction. A key limitation is the absence of harmonised international exposure standards, which results in considerable variability in permissible limits and enforcement practices across countries. There is also limited research assessing the real-world implementation and effectiveness of silica dust regulations in countries with limited institutional capacity. In addition, the influence of cultural and organisational factors remains underexplored in the context of regulatory compliance. Seasonal and climatic factors that influence dust levels have also not been sufficiently integrated into risk management strategies, especially in regions where adaptive practices are inconsistently applied.

As illustrated in Figure 4, significant gaps also exist in underrepresented regions, such as parts of Africa (e.g., Ghana [63], Uganda [67], South Africa [68]), Southeast Asia (e.g., Malaysia [69]), and Latin America (e.g., Brazil [70]), where either no regulation exists or enforcement is limited. In these contexts, high reliance on informal construction sectors, insufficient dust suppression measures, and limited worker training contribute to sustained elevated silica exposure risks, underscoring the need for targeted, region-specific interventions.

3.3. Current Silica Dust Control Measures

A comprehensive analysis of studies across diverse categories offers a panoramic view of silica dust control measures in the construction industry. It illuminates the evolution of control strategies, from traditional methods to cutting-edge technologies, and tracks advancements in measurement techniques that enable more precise exposure assessments. This review underscores the significant impact of regulatory changes on driving industry-wide improvements in silica exposure mitigation and reveals the interconnected nature of engineering controls, work practices, and policy interventions in shaping a safer work environment. Figure 5 illustrates the predominant silica dust control measures currently employed in the construction industry, as identified through systematic content analysis of peer-reviewed publications. The analysis employed ATLAS.ti 9 software to code and categorise control measures based on their frequency of mention and documented effectiveness in field studies. The following subsections examine the technical specifications and implementation requirements of these evidence-based control methods.

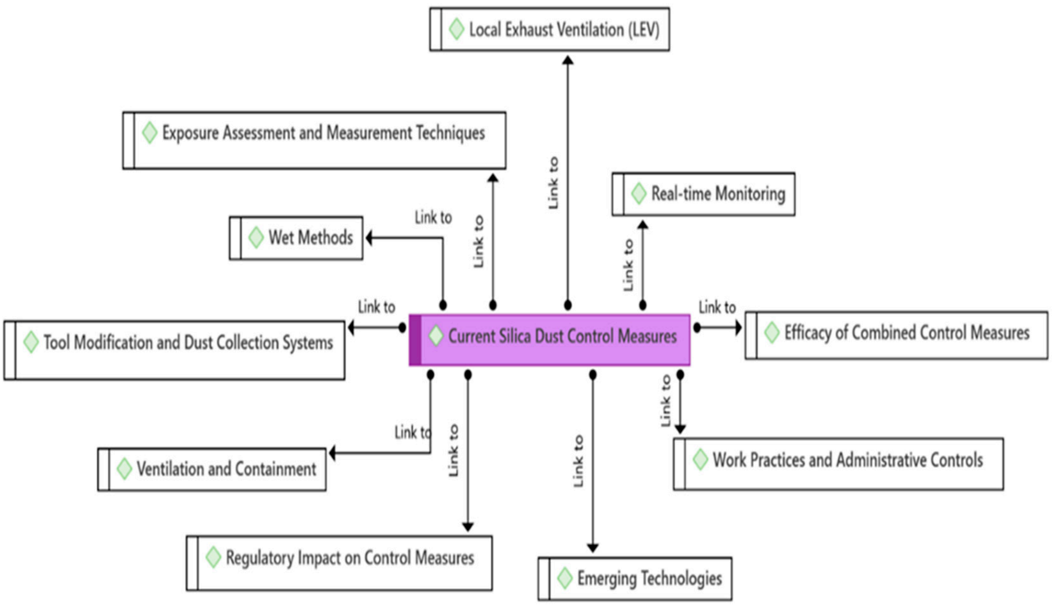

Figure 5. Predominant silica dust control measures identified in the reviewed literature.

3.3.1. Local Exhaust Ventilation

Local exhaust ventilation (LEV) has emerged as an important engineering control measure for reducing silica exposure in the construction industry. This specialised system is designed to capture and remove airborne contaminants directly at their source, significantly reducing the risk of worker exposure to hazardous substances. Over the past two decades, numerous studies have consistently demonstrated LEV's effectiveness across various construction tasks and environments. Healy et al. [71] assessed on-tool shrouds for controlling silica dust in stone restoration, showing significant reductions in worker exposure. Collingwood and Heitbrink [13] examined LEV systems for removing mortar from masonry joints—a high-risk construction activity where workers remove deteriorated mortar between bricks or stones using powered tools, often generating significant silica dust. Heitbrink and Bennett [72] investigated silica exposure control during tuckpointing (the process of repairing brick mortar joints), demonstrating that LEV systems can significantly reduce worker exposure to hazardous silica dust, though their effectiveness varies based on specific work conditions and system configuration.

These examples from previous studies paint a comprehensive picture of LEV's role in silica exposure control, demonstrating its effectiveness across various construction tasks, from drilling and cutting to grinding and restoration. The research also shows the evolution of LEV technology, from standalone systems to integrated tool designs, reflecting the industry's ongoing efforts to enhance worker protection [73].

While LEV has been widely proven to be effective in reducing silica exposure, its success depends on proper implementation, maintenance, and use. Existing studies have primarily focused on short-term exposure reduction during specific tasks, with limited research assessing the long-term health outcomes associated with sustained LEV use. In addition, the effectiveness of LEV systems is highly dependent on factors such as capture velocity, hood design, and worker training, which are often underreported or inconsistently evaluated in the literature. Future research should focus on optimising these factors and exploring ways to increase the adoption and correct use of LEV systems across the construction industry. This could involve developing user-friendly designs, improving integration with commonly used tools, and creating comprehensive training programmes. Studies on the long-term health outcomes of workers using LEV systems could also provide valuable data on the lasting benefits of this control measure.

3.3.2. Wet Methods

Several studies have demonstrated the effectiveness of wet methods in controlling silica dust exposure across various tasks and environments. Cooper, Johnson, and Phillips [14] investigated dust suppression in artificial stone countertop cutting, showing significant reductions in RCS exposure. Summers and Parmigiani [74] explored an innovative water-soluble additive for dust control in concrete-cutting chainsaws, enhancing the efficacy of traditional water applications. Akbar-Khanzadeh et al. [75] compared wet grinding to ventilated and uncontrolled grinding for indoor concrete work, highlighting the superior performance of wet methods.

The reviewed studies collectively reveal the versatility of wet methods across tasks like cutting, grinding, and large-scale roadway construction [75]. They also demonstrate a progression from basic water application to more advanced misting systems and chemical additives. While wet methods are generally effective in reducing silica exposure, their success depends on correct implementation. Key factors such as water flow rate, nozzle design, and worker training significantly influence their performance but are often underreported or not standardised across studies. There is also limited research on their combined effectiveness when used alongside other control measures, such as LEV and PPE. Future research should aim to optimise these implementation variables, evaluate combined control strategies, and explore barriers to adoption in diverse construction environments.

3.3.3. Tools Maintenance, Modifications, and Dust Collection Integration

Tool modification and dust collection systems have become essential strategies for mitigating RCS exposure in construction. Several researchers have explored innovative approaches to integrate dust control mechanisms directly into tools, significantly improving worker safety. Garcia, Jones, Echt, and Hall [73] evaluated an aftermarket LEV device for powered saws, demonstrating the potential for retrofitting existing tools. Qi, Echt, and Gressel [76] investigated dust generation rates from cutting fibre cement siding with different tools, highlighting the importance of tool selection in dust control. Carty et al. [77]

studied how bit wear affects silica dust generation in hammer drills, emphasising the need for regular tool maintenance.

The reviewed studies collectively showcase the evolution and potential of tool modification and integration with dust collection systems. They highlight a clear trend toward integrating dust control mechanisms directly into tools to improve effectiveness, usability, and worker compliance. The findings also underscore the importance of task-specific solutions, suggesting different construction activities require tailored approaches to dust control, which further necessitates ongoing research and development to address the diverse and evolving range of tasks in the industry. However, few studies address the practical challenges of retrofitting tools in lower-resourced settings, where financial and logistical barriers may hinder widespread adoption. The impact of maintenance practices and operator training on control system performance is also underexplored. Considering the flexible and adaptable nature of these measures, future research should focus on optimising integration strategies, evaluating their performance over time, and identifying barriers to broader industry implementation.

3.3.4. Exposure Assessment and Measurement Techniques

Significant advancements in exposure assessment and measurement techniques have been critical in understanding and mitigating RCS exposure in the construction industry. Stacey, Thorpe, Roberts, and Butler [10] employed a mobile high-flow rate sampler for measuring respirable silica across various environments, demonstrating improved portability and versatility in sampling methods. Sauvé, Beaudry, Bégin, Dion, Gérin, and Lavoué [9] developed statistical models for silica exposure estimation during construction activities, enhancing the ability to predict and assess exposure risks. Peters, Vermeulen, Portengen, Olsson, Kendzia, Vincent, Savary, Lavoué, Cavallo, and Cattaneo [42] created models for quantitative exposure assessment in case–control studies, contributing to understanding long-term health impacts.

These studies highlight the progress in accurately quantifying and characterising silica exposure risks. Advancements include improving sampling methods, employing sophisticated statistical modelling, and establishing comprehensive exposure databases. However, several limitations persist in accurate exposure measurement due to the dynamic nature of construction sites, variability in tasks, and changing environmental conditions. There is limited validation of real-time monitoring technologies under field conditions, and little standardisation across studies in data collection protocols, which hinders cross-study comparisons and regulatory benchmarking. Future research should focus on enhancing real-time dust monitoring technologies, improving the durability of LEV systems and dust collection equipment under harsh construction conditions, and developing more accurate predictive models for worker exposure assessment. Furthermore, exposure assessment methods must evolve alongside emerging construction techniques and materials. In addition, standardised measurement protocols are needed to ensure consistency and reliability across different occupational settings. These improvements could significantly enhance the capacity to develop more effective data-driven strategies to protect worker health and safety in construction.

3.3.5. Real-Time Monitoring

The construction industry has made significant steps in monitoring and controlling exposure to hazardous substances, particularly RCS. Research in this field has highlighted both persistent risks and innovative monitoring techniques. Beaucham et al. [78] conducted a multi-state assessment of silica exposure among outdoor workers, providing valuable insights into regional variations and environmental factors. Lappi, Radnoff, and Karpluk [79] examined silica exposure and silicosis in Alberta, Canada, contributing to understanding long-term health impacts.

Fan, Wong, Shen, Lu, Wang, Yu, and Shen [8] tested "Dust Bubbles"—an innovative dust capture system that creates a negative pressure zone around the drill bit using a plastic shroud—for concrete drilling dust control, demonstrating a novel approach to real-time exposure management. Real-time monitoring, once aspirational, is increasingly becoming a practical tool in combating occupational silica exposure. Integrating wearable sensors, artificial intelligence, and big data analytics provides significant potential for developing predictive exposure models and proactive interventions.

However, the effectiveness of these technologies in complex and variable construction environments remains underexplored. There is limited validation of real-time systems under field conditions, and challenges persist in data interpretation, worker compliance, and integration into routine safety practices. Technology alone is not sufficient. Effective implementation requires a holistic approach encompassing worker education, management commitment, and ongoing research.

3.3.6. Ventilation and Containment

Ventilation and containment strategies remain critical in controlling RCS exposure, particularly in construction and heavy industries. Several studies have demonstrated the effectiveness of innovative engineering controls in reducing worker exposure across diverse work environments using these strategies. Meeker et al. [80] evaluated engineering controls for masonry cutting and tuckpointing, highlighting task-specific solutions. Shepherd and Woskie [81] studied dust control in concrete saw cutting, addressing a common source of silica exposure. Golla and Heitbrink [82] investigated control technology for wet abrasive blasting, highlighting the evolution of containment strategies.

A clear trend toward more sophisticated, integrated solutions for ventilation and containment that address the multifaceted challenges of silica exposure is evident in the reviewed studies. This is a rapidly advancing field, from targeted LEV systems to comprehensive air quality management. However, research on the performance of these systems under variable on-site conditions remains limited. There is also a lack of standardised metrics to evaluate system effectiveness across different tasks and settings, as well as limited exploration of cost-effectiveness and user acceptance in real-world applications. Future developments may include smart ventilation systems that adapt in real time to changing conditions and new materials for inherent suppression of dust generation.

3.3.7. Work Practices and Administrative Controls

Recent research has made significant progress in evaluating and improving work practices and administrative controls to address the challenge of controlling worker exposure to RCS. Muianga et al. [83] developed a checklist model for small-scale demolition operations, providing a practical tool for risk assessment and control. Radnoff, Todor, and Beach [84] examined occupational exposure at Alberta work sites, offering insights into regional variations and industry-specific challenges. van Deurssen, Meijster, Oude Hengel, Boessen, Spaan, Tielemans, Heederik, and Pronk [38] evaluated a multidimensional intervention to reduce quartz exposure among construction workers, demonstrating the effectiveness of comprehensive approaches.

The trend of the reviewed studies is toward more nuanced, evidence-based approaches, from task-specific techniques to comprehensive risk assessment tools. Integrating advanced work practices with emerging technologies and real-time monitoring systems holds promise for further reducing silica exposure risks. However, gaps remain in evaluating the long-term effectiveness and sustainability of administrative controls across different construction settings. Research is also limited on how organisational culture, worker perceptions, and communication strategies influence adherence to safe work practices. Successful implementation requires ongoing worker training, management commitment, and regular evaluation of control measures.

3.3.8. Efficacy of Combined Control Measures

The effectiveness of combined control measures relies on their multifaceted approach. Akbar-Khanzadeh et al. [85] evaluated three integrated dust control methods during manual concrete surface grinding: LEV, water suppression, and general ventilation. Their study demonstrated that combining LEV with water suppression reduced respirable dust concentrations by 97% compared to using no controls, while LEV alone achieved an 88% reduction, and water suppression alone reached a 90% reduction. Middaugh et al. [86] assessed a combination of water suppression systems and LEV for cut-off saws, finding that proper water flow rates (0.5–2.0 L/min) combined with modified cutting techniques (such as proper saw positioning and cut depth control) reduced respirable dust exposure by up to 95% compared to uncontrolled cutting. Beamer et al. [87] investigated misting controls for brick cutting, showcasing how water-based suppression can complement other control strategies.

These studies collectively demonstrate the evolution in dust control from single-method approaches to integrated strategies, supported by quantitative exposure reduction data: water suppression alone (90% reduction), LEV systems (88% reduction), and combined methods achieving up to 97% reduction in respirable dust exposure. They underscore the importance of combining engineering controls, work practice modifications, and administrative measures to achieve significant reductions in silica exposure. The research also reveals that the efficacy of combined measures often exceeds the sum of individual interventions, suggesting a synergistic effect. This approach not only enhances exposure reduction but also provides redundancy, ensuring protection even if one control measure fails. As the field advances, the focus on evaluating and optimising combined control measures promises to yield more effective and sustainable solutions for protecting worker health across diverse construction settings and tasks. However, few studies have evaluated their long-term sustainability or adaptability under varying site conditions, especially in small-scale or informal sectors. Further research is needed to optimise combined approaches for diverse environments and to support their practical implementation.

3.3.9. Emerging Technologies

Emerging technologies are revolutionising silica exposure prevention and management in occupational settings. Several researchers have explored innovative solutions that promise to transform the approach to workplace silica-related risks. Johnson et al. [88] evaluated integrated dust control systems for stone countertop fabrication that combined automated water feed systems with tool-mounted LEV (flow rate: 2.2–2.8 m^3/min) and real-time dust monitoring sensors. Their study showed that these automated controls reduced RCS exposure by 92% compared to traditional manual water spraying, while smart sensors provided immediate feedback to adjust water flow rates based on cutting speed and material density.

Rempel, Barr, and Cooper [89] studied hollow-bit LEV for concrete drilling, showcasing innovative tool designs for exposure reduction. Carlo et al. [90] examined automated water–feed systems and optimised blade design (including segmented diamond blades with modified gullet depth) to minimise dust generation when cutting concrete roofing tiles, finding that the combination reduced respirable dust concentrations by 85% compared to conventional wet cutting methods.

These quantitatively validated interventions demonstrate how well-designed engineering controls can reduce silica exposure by 85–97% in high-risk construction and manufacturing processes, as documented through rigorous field testing. These technologies protect worker health and improve productivity by reducing cleanup time and maximising visibility during cutting operations. As measurement and control technologies continue advancing, opportunities emerge for real-time exposure monitoring and automated dust suppression systems that can further enhance workplace safety in silica-exposed environments.

Current research on emerging technologies remains largely focused on technical performance, with limited attention to their real-world adoption, cost-effectiveness, and integration into routine construction workflows. There is a need for studies that assess long-term durability, user training requirements, and scalability in resource-constrained and informal construction environments. Additionally, regulatory alignment and digital infrastructure are needed to support the successful implementation and performance of smart monitoring systems.

3.3.10. Regulatory Impact on Control Measures

Regulatory changes have significantly impacted silica exposure control in occupational settings, driving advancements in health and safety practices. Recent studies highlight the far-reaching implications of these regulatory initiatives across various industries. Li et al. [91] examined the construction industry's adaptation to OSHA's updated silica standard, revealing how regulatory changes spur innovation in control technologies and work practices. Doney et al. [92] utilised OSHA compliance data to estimate worker exposure, demonstrating the value of regulatory reporting in understanding and addressing exposure risks. Deslauriers and Redlich [93] explored the implications of the new OSHA silica standard for pulmonologists, underscoring the broader healthcare implications of occupational safety regulations.

These studies collectively illustrate the profound impact of regulatory initiatives on silica exposure prevention. Regulations have emerged as powerful catalysts for change, driving innovation in control technologies, reshaping industry practices, and transforming workplace cultures. The research also highlights challenges in regulatory compliance and the need for ongoing education and support for employers and workers. As global awareness of silica-related health risks grows, the evolution of regulatory frameworks promises further efforts to protect worker health across diverse industries and geographical contexts. Integrating emerging technologies with regulatory compliance strategies may offer new opportunities for more effective and efficient silica exposure control.

Despite their transformative role, there is limited evaluation of regulatory frameworks in terms of enforcement effectiveness and consistency across regions, particularly in low- and middle-income countries. Practical barriers to implementation include cost, limited access to compliant technologies, and inadequate training. In addition, delays in regulatory updates may hinder the timely integration of emerging scientific evidence, reducing the overall responsiveness of regulatory systems. Further research is needed to assess regulatory impact across diverse contexts and to explore opportunities for standardisation and equitable enforcement.

3.4. Worker Awareness and Safety Practices

The analysis of the reviewed articles reveals the multifaceted nature of silica exposure management in construction. Worker awareness and safety practices are shaped by a complex interplay of factors, including knowledge levels, training efficacy, risk perception, proper PPE utilisation, procedural compliance, worker engagement, and organisational safety culture. The research underscores the necessity for holistic approaches that simultaneously address individual behaviours and systemic organisational factors. Effective strategies must integrate targeted education, innovative training methods, robust safety protocols, and a supportive organisational framework. Promoting a culture of shared responsibility and continuous improvement, the industry can significantly enhance safety practices and substantially mitigate silica exposure risks, ultimately safeguarding worker health in this high-risk sector. Figure 6 provides a comprehensive visualisation of worker awareness and safety practices currently implemented in the construction industry to mitigate silica exposure risks.

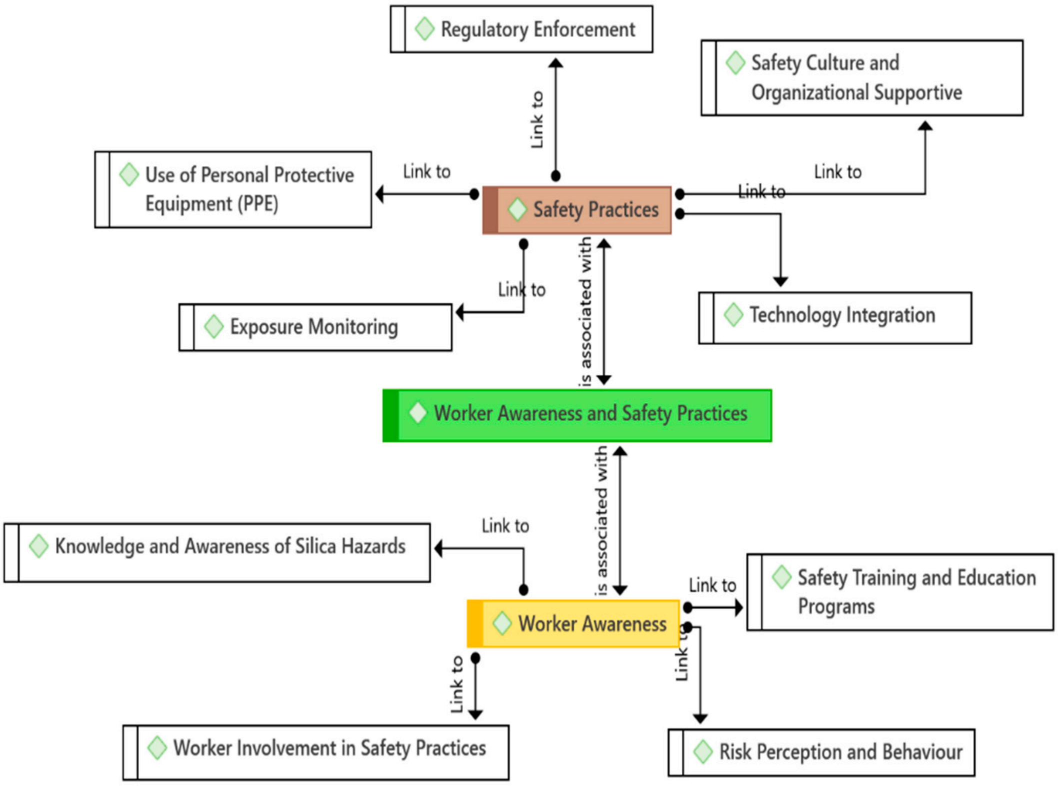

Figure 6. Summary of worker awareness and safety practices for silica exposure prevention.

3.4.1. Enhanced Knowledge and Awareness of Silica Hazards

The effectiveness of silica exposure control measures is intrinsically linked to the level of awareness and understanding among workers and employers. Recent studies have emphasised the importance of worker awareness and safety practices in mitigating silica exposure risks. Gaviola, Nicolaou, Sharma, Chandyo, Parker, Shrestha, Das, Ramachandran, Thygerson, and Beres [24] conducted a comprehensive assessment of knowledge, attitudes, and practices regarding respirable silica exposure and PPE use among brick kiln workers in Nepal. Their findings underscored the need for targeted educational interventions to enhance worker awareness. Cole, Glass, Bence, Pisaniello, Knott, Rowett, and Johnson [23] examined prevention strategies for the occupational silicosis epidemic in Australia, emphasising the role of informed workplace health risk assessors in shaping effective safety practices. Hayashi, Li, Sussman, Okuzono, Viswanath, and Kawachi [25] conducted a scoping review of interventions to improve the occupational safety and health of construction workers, suggesting including best practices for enhancing worker awareness and safety practices.

Key findings indicate that worker awareness significantly influences adherence to safety practices and the overall effectiveness of dust control measures. Moreover, informed workplace health risk assessors have been pivotal in shaping robust safety protocols. The research emphasises the need for ongoing, tailored education initiatives that address the specific needs of diverse worker populations and industry sectors. Equipping workers and employers with up-to-date information can enhance the implementation of effective control measures and ultimately safeguard worker health against the pervasive threat of silica exposure.

3.4.2. Improved Safety Training and Education Programs

The development and implementation of effective safety training and education programs are essential elements in reducing occupational silica exposure rates. The latest research highlights the crucial role of robust safety training and education programs in combating silica-related occupational hazards. Beard et al. [94] studied respirable dust and crystalline silica concentrations among workers at a brick kiln in Nepal, which likely included recommendations for improved training programs. Fluck et al. [95] examined the disparity in the risk of exposure to RCS dust among non-manual and manual employees in the construction industry, potentially highlighting the need for tailored training programmes. Mastrantonio et al. [96] assessed exposure to inhalable and respirable dust in post-earthquake construction sites, potentially providing insights into effective safety education strategies in challenging environments.

These studies emphasise the critical role of safety training and education programs in combating silica-related occupational health risks. They highlight the need for innovative, engaging, and targeted educational initiatives that address the specific needs of diverse worker populations across various industries and education settings. As the understanding of effective educational strategies evolves, so must the approaches to developing and implementing training programmes, ensuring that workers are empowered with the knowledge and skills necessary to protect their health in silica-exposed environments.

3.4.3. Enhanced Risk Perception and Behaviour

Understanding and influencing worker risk perception and behaviour are crucial elements in the effective management of silica exposure risks. Ahimbisibwe, Tumusiime, Muteebwa, Mupere, and Andia Biraro [67] investigated the prevalence of pulmonary tuberculosis among casual labourers working in selected road construction sites, which likely addressed risk perception and behaviour. Gliga, Grahn, Gustavsson, Ljungman, Albin, Selander and Broberg [11] examined short and long-term associations between serum proteins linked to cardiovascular disease and particle exposure among construction workers, potentially influencing risk perception. Yi et al. [97] analysed the current status, trends, and predictions regarding the burden of silicosis in 204 countries and territories, which could impact risk perception and behaviour on a global scale.

These studies underscore the importance of understanding and addressing risk perception and behaviour in silica exposure prevention. They highlight the complex interplay between individual knowledge, attitudes, and practices and the broader organisational and cultural contexts in which workers operate. Moving forward, integrating behavioural insights into comprehensive silica management strategies promises to enhance the effectiveness of existing control measures and drive meaningful improvements in occupational health outcomes. Addressing the human factors that influence exposure risks can create more resilient and effective systems for protecting worker health in silica-exposed environments.

3.4.4. Use of Personal Protective Equipment (PPE)

PPE serves as a crucial last line of defence in protecting workers from RCS exposure. Gaviola, Nicolaou, Sharma, Chandyo, Parker, Shrestha, Das, Ramachandran, Thygerson, and Beres [24] specifically addressed PPE use among brick kiln workers in Nepal. Cothern, Autenrieth, and Brazile [48] evaluated RCS exposure for construction tasks, likely including

PPE effectiveness. Jacobs, R and Tarpey [47] reported on exposures to RCS during construction tasks and provided guidance for harmonising future research, which presumably includes PPE recommendations.

Furthermore, these studies underscore the critical role of PPE in silica exposure prevention while highlighting the challenges associated with ensuring consistent and effective use. They emphasise the need for comprehensive approaches that address the technical aspects of PPE selection and performance as well as the human factors that influence compliance and effectiveness. Therefore, the integration of innovative PPE designs, improved comfort and usability features, and advanced training methodologies promises to enhance the effectiveness of personal protection strategies. Addressing the technical specifications and behavioural compliance factors of PPE use can enhance respiratory protection effectiveness and improve occupational health outcomes in industries with silica exposure risks.

3.4.5. Regulatory Enforcement

Regulatory measures play a pivotal role in shaping industry practices and driving improvements in worker protection against RCS exposure. Adherence to established safety procedures is crucial in mitigating the risks of RCS exposure. Recent research has shed light on the complex factors influencing compliance and the impact of regulatory changes on worker behaviour across various industries. Cole, Glass, Bence, Pisaniello, Knott, Rowett, and Johnson [23] studied prevention strategies for the occupational silicosis epidemic in Australia, likely evaluating the effectiveness of current regulatory measures. Delabre et al. [98] investigated occupational exposure to silica dust in France, presumably examining the impact of regulatory frameworks. Rupani [5] discussed challenges and opportunities for silicosis prevention and control, likely addressing the role of regulatory bodies in ensuring compliance.

These studies demonstrate that consistent worker adherence to safety protocols significantly enhances the effectiveness of silica dust control measures, directly reducing exposure risks and improving health outcomes. They highlight the complex interplay of regulatory, organisational, and individual factors on adherence to safety procedures. Therefore, the development of more nuanced, context-specific strategies for improving compliance promises to enhance the effectiveness of silica exposure control efforts. Addressing the barriers to adherence and leveraging insights from behavioural sciences can create more robust systems for protecting worker health in silica-exposed environments.

3.4.6. Enhanced Worker Involvement in Safety Practices

The active participation of workers in developing, implementing, and refining safety practices has emerged as a crucial factor in effective silica exposure control. Tuomi, Johnsson, Heino, Lainejoki, Salmi, Poikkimäki, Kanerva, Säämänen, and Räsänen [64] focused on managing quartz exposure in apartment buildings and infrastructure construction tasks, likely involving worker participation. Filip, Abanda, and Fru [51] examined construction 3D printing in reducing the incidence of long-latency respiratory diseases, potentially highlighting worker involvement in new technologies. Wang, Yao, Sun, Yang, and Deng [58] reviewed exposure to construction dust and health impacts, presumably addressing worker engagement in dust control measures.

The reviewed studies evidently demonstrate the transformative potential of meaningful worker involvement in safety practices. Actively engaging workers as partners in the development and implementation of safety measures enables organisations to establish more effective, sustainable, and widely adopted approaches to silica exposure control. This participatory paradigm enhances the quality of safety practices and fosters a culture of shared responsibility and continuous improvement in occupational health and safety.

3.4.7. Enhanced Safety Culture and Organisational Supportive

The development of a robust safety culture and supportive organisational structures is a crucial element in the successful implementation of silica exposure control measures. Cole, Glass, Bence, Pisaniello, Knott, Rowett, and Johnson [23] researched silicosis prevention strategies in Australia, likely addressing organisational culture. Hayashi, Li, Sussman, Okuzono, Viswanath, and Kawachi [25] reviewed interventions to improve occupational safety and health of construction workers, presumably including safety culture aspects. Boadu, Okeke, Boadi, Bonsu, and Addo [63] conducted a systematic narrative review of work-related respiratory health conditions among construction workers, potentially addressing organisational support for health initiatives.

These studies reveal that a robust safety culture, driven by leadership commitment and integrated organisational systems, fundamentally shapes the success of silica exposure prevention programs. When organisations prioritise worker protection through clear policies, adequate resources, and consistent communication, protective measures become embedded in daily operations rather than treated as optional procedures. Therefore, developing strategies to enhance safety culture and optimise organisational factors can significantly improve silica exposure controls. By addressing these foundational elements, organisations can create more resilient and effective systems for protecting worker health, fostering a workplace environment where safety is seamlessly integrated into all aspects of operations.

3.4.8. Enhanced Exposure Monitoring

Recent advancements in exposure monitoring technologies and methodologies have revolutionised the ability to assess and manage silica-related occupational health risks. These innovations enable more accurate, timely, and comprehensive evaluation of workplace silica exposures across various industries. Beard et al. (2024) [94] studied respirable dust and crystalline silica concentrations among brick kiln workers in Nepal, likely employing cutting-edge monitoring techniques. Couture, Charuvil Elizabeth, Lefsrud, and Sattari [17] evaluated workplace exposure to RCS in Alberta's road construction industries, presumably utilising advanced sampling and analytical methods. Rey-Brandariz et al. [99] conducted a systematic review on occupational exposure to RCS and lung cancer, synthesising findings from various exposure monitoring studies and potentially highlighting emerging technologies.

Integrating these enhanced monitoring techniques with artificial intelligence, big data analytics, and IoT devices promises even more sophisticated exposure assessment capabilities. Real-time data analysis, predictive modelling, and automated risk alerts could further revolutionise silica exposure management. Wearable sensors, for instance, could provide continuous, personalised exposure data, while AI-powered systems could identify exposure patterns and predict high-risk scenarios.

However, improved monitoring alone is insufficient. The true value of these advancements lies in their ability to inform and drive more effective control measures and preventive strategies. Future developments will likely focus on creating more holistic and responsive systems that integrate monitoring data with other aspects of occupational health management. This could include adaptive ventilation systems that respond to real-time exposure data, or personalised worker training programs based on individual exposure profiles.

3.4.9. Enhanced Technology Integration

The integration of cutting-edge technologies is revolutionising silica exposure prevention and management in occupational health and safety. Recent research demonstrates how innovative technological applications are enhancing risk mitigation, exposure monitoring, and worker health protection across various industries. Filip, Abanda, and Fru [51] explored how construction 3D printing can reduce long-term respiratory diseases, highlighting the role of advanced manufacturing techniques in minimising dust generation. Damilos et al. [100] provided an overview of Industry 4.0 tools and challenges for safety evaluation and exposure assessment, addressing technological advancements in silica exposure control.

These studies underscore the transformative potential of technology in addressing workplace silica exposure challenges. Technologies ranging from VR simulations and advanced diagnostics to innovative dust control solutions and smart PPE can enhance the ability to prevent, detect, and manage silica-related health risks. Integrating artificial intelligence, the Internet of Things (IoT), and advanced data analytics offers even greater promise, potentially leading to real-time, AI-driven exposure monitoring systems and IoT-enabled PPE that provide personalised risk assessments. However, effectively implementing these technologies requires significant investment in infrastructure, training, and interdisciplinary collaboration. As these innovations evolve and become more integrated into workplace safety systems, they can create more proactive, precise, and effective strategies for protecting worker health, ultimately leading to safer work environments and improved long-term health outcomes in silica-exposed industries. However, the real-world adoption of these technologies, particularly in informal or resource-constrained construction settings, remains limited. Barriers such as high initial costs, the need for ongoing maintenance, limited digital infrastructure, and low technical capacity often hinder implementation. These challenges are especially pronounced in developing countries and small-scale construction environments, where safety oversight and funding are minimal. Evaluating cost-effectiveness, simplifying user interfaces, and tailoring solutions to local contexts will be essential to ensure equitable uptake and impact.

4. Conclusions

This systematic review of 143 studies spanning two decades (2004–2024) reveals transformative progress in managing RCS hazards within the construction industry, while also highlighting persistent challenges that require urgent attention to achieve the United Nations Sustainable Development Goals (SDGs). The findings demonstrate a paradigmatic shift from basic exposure assessment techniques toward sophisticated, technology-driven approaches that integrate real-time monitoring, predictive analytics, and comprehensive health surveillance systems, directly supporting SDG 3’s objective of ensuring healthy lives and promoting well-being for all.

This review documents remarkable advancements in detection and characterisation methodologies, with emerging technologies such as wearable sensors, IoT-based monitoring systems, and machine learning algorithms revolutionising exposure assessment. These innovations have enabled unprecedented precision in quantifying RCS exposures and implementing proactive risk management strategies that align with SDG 3.9’s target to substantially reduce deaths and illnesses from hazardous chemicals. Engineering controls, particularly local exhaust ventilation, wet suppression, and modified tool designs, have demonstrated substantial efficacy in reducing exposures, with some interventions achieving over 90% reduction when properly implemented and maintained. However, the uptake of these technologies remains inconsistent, creating barriers to achieving SDG 8.8’s commitment to safe working environments. Adoption rates vary sharply, with developed regions benefiting from advanced systems while resource-constrained areas rely on basic protective measures. This divide perpetuates occupational health inequities, particularly affecting migrant workers and those in precarious employment.

Critical findings reveal pronounced regional variations in regulatory frameworks, enforcement capacity, and infrastructure that influence intervention effectiveness and progress toward SDG targets. While some jurisdictions have implemented stringent exposure limits and comprehensive monitoring requirements supporting SDG 3.9's objectives, others lack basic oversight or enforcement, creating gaps in worker protection. This regulatory fragmentation presents complex challenges for multinational construction projects and migrant worker populations, who may experience varying levels of protection depending on location and employment conditions, directly contradicting SDG 8.8's emphasis on ensuring safe working environments for all workers, including migrants. The evidence underscores the need for context-specific solutions that consider local economic constraints, cultural factors, and infrastructural limitations while maintaining alignment with SDG principles of leaving no one behind. Uniform strategies often fail, necessitating adaptive approaches that balance technological sophistication with practical feasibility.

The reviewed literature expands our understanding of silica-related health impacts beyond respiratory diseases to include cardiovascular disorders, autoimmune conditions, and systemic inflammatory responses, reinforcing the importance of SDG 3.9's comprehensive approach. This broader health profile necessitates health surveillance protocols that monitor multiple organ systems and provide long-term follow-up for exposed workers. The findings support integrated occupational health management that addresses both immediate exposure reduction and long-term health protection, contributing to sustainable urban development (SDG 11) by promoting safer construction practices.

Moving forward, sustainable silica exposure management requires strategies that integrate technological innovation with effective regulatory oversight, comprehensive worker education, and culturally sensitive implementation approaches to accelerate progress toward the 2030 Agenda for Sustainable Development. This review identifies critical needs for standardised assessment protocols, affordable control technologies, and enhanced international cooperation to address regulatory disparities. Progress will depend on continued investment in research and development, particularly for affordable solutions to diverse economic contexts, ensuring that SDG 8.8's commitment to decent work extends globally. Strengthening technical expertise through training and promoting knowledge exchange between regions will be essential for achieving equitable protection standards globally, supporting the interconnected nature of SDGs 3, 8, and 11.

This review concludes that while significant progress has been made, comprehensive hazard control demands sustained action to overcome technological, regulatory, and socioeconomic barriers, supporting the SDG framework's vision of development, which leaves no worker behind.

5. Future Directions

Organisations must adopt integrated and multifaceted strategies for effective silica exposure control, combining technical, administrative, and behavioural interventions. As the construction workforce grows increasingly diverse, multilingual and culturally responsive training programmes should be updated regularly to reflect current research findings and technological advancements. Interactive and hands-on training methods, such as virtual reality and simulation-based learning, have demonstrated superior outcomes compared to traditional classroom-based approaches, significantly improving worker engagement and compliance with safety measures. Successful silica dust control relies heavily on clearly defined and consistently enforced organisational policies. These policies should include standardised protocols for exposure control, regular monitoring and documentation practices, and robust incident reporting and investigative procedures. Regulatory authorities must ensure that the implementation of stricter exposure limits aligns with the industry's capacity to comply, particularly concerning the availability and practicality of measurement tools and monitoring resources. To ensure compliance with stricter regulatory limits, it is important that implementation aligns with practical capabilities in the field, including the availability and usability of validated measurement tools. Investment in advanced monitoring equipment and control technologies, coupled with routine maintenance, enhances policy effectiveness and compliance outcomes.

Technological advancements, particularly real-time monitoring systems, have significantly transformed silica exposure management, enabling proactive interventions and precise control measures. However, implementing these innovations must consider regional variations in infrastructure, technical expertise, and cultural contexts. Interdisciplinary collaborations will be key to integrating these advanced technologies, maximising their potential in mitigating exposure risks and safeguarding worker health across varied construction environments. Occupational health surveillance programmes should expand to monitor long-term health outcomes, including emerging risks such as cardiovascular diseases and autoimmune diseases linked to RCS. Actively involving workers in the development and refinement of safety practices is crucial for sustainable silica exposure control. Organisations that promote a strong safety culture, driven by leadership commitment and worker participation, achieve significantly better outcomes in exposure risk reduction. Encouraging active worker engagement in safety measures can improve compliance, foster collective responsibility, and ultimately contribute to more sustainable and resilient occupational health and safety outcomes in high-risk construction settings where silica exposure remains a persistent challenge.

6. Limitations of This Study

Despite providing a comprehensive synthesis of technological and regulatory advances in controlling RCS, this systematic review has some inherent limitations that should be acknowledged. Firstly, this review was restricted to publications identified through Scopus, PubMed, and Google Scholar databases, which could introduce potential biases related to indexing, publication selection, and reporting, as not all relevant studies may be captured within these databases.

Secondly, this review included only studies published in English, which may overlook valuable insights or technological advancements reported in other languages, potentially limiting the global representativeness of the findings. Thus, future reviews incorporating additional languages could offer more inclusive global insights and enhance applicability across different contexts.

Additionally, the exposure limits and regulatory standards reported in this review were drawn solely from selected published studies. This may not fully reflect all current regional standards or ongoing regulatory adjustments not captured within the reviewed literature, thus limiting the scope of comparative analysis and conclusions regarding international regulatory practices.

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