Research Article

Occupational Medicine In The Prevention And Management Of Workplace-Related Cancer: Mechanisms, Strategies And Emerging Challenges

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Abstract

Background: Occupational cancer represents a major but underrecognized public health challenge, contributing to an estimated 8% of global cancer cases. Workers in high-risk industries, such as construction, chemical manufacturing, and mining, face prolonged exposure to carcinogens including asbestos, benzene, and aromatic amines.
Objectives: This review examines the role of occupational medicine in identifying, managing, and preventing cancers linked to workplace exposures, while addressing diagnostic advances, regulatory frameworks, and preventive strategies.
Methods: A narrative review of existing literature, regulatory documents, and surveillance data was conducted, focusing on biological mechanisms of carcinogenesis, industry-specific risks, diagnostic innovations, and prevention policies.
Results: Occupational carcinogenesis involves mechanisms such as genotoxicity, oxidative stress, epigenetic alterations, and chronic inflammation. Key carcinogens include vinyl chloride and chromium VI. Advances in biomarker analysis and health surveillance enhance early detection and risk assessment. Regulatory measures, ranging from IARC classifications to national compensation laws, provide frameworks for protection but face implementation barriers, especially in low- and middle-income countries. Preventive strategies based on the hierarchy of controls, health education, and green chemistry remain central, while emerging concerns include underreporting, nanoparticle exposure, and psychosocial impacts.
Conclusions: A multidisciplinary approach is essential for reducing the burden of occupational cancer. Future directions include digital surveillance systems, personalized occupational medicine, and stronger global collaborations to ensure workplace safety and equitable health outcomes.

Keywords: Occupational cancer, carcinogenic exposure, occupational medicine, cancer prevention, personalized occupational medicine.

1. Introduction

Cancer continues to be a major global health challenge, ranking among the leading causes of morbidity and mortality. While lifestyle and genetic factors contribute significantly to its incidence, a substantial proportion of cancers are linked to environmental and occupational exposures [1]. The International Labour Organization (ILO) estimates that more than 600,000 deaths annually are attributed to occupational cancer, making it one of the deadliest work-related health outcomes worldwide [2]. This staggering statistic highlights the urgency of integrating cancer prevention into occupational health policies and practices.

Occupational medicine, a specialized branch of preventive medicine, is dedicated to safeguarding the health of workers by identifying, mitigating, and managing workplace hazards including those that may lead to carcinogenesis [3]. Its role extends from clinical assessment and risk evaluation to regulatory compliance, worker education, and long-term health monitoring. As industrial processes become more complex and globalized, the challenge of managing exposure to carcinogens like asbestos, benzene, and formaldehyde has intensified, particularly in low- and middle-income countries where regulatory frameworks are often weak or poorly enforced [4].

Occupational cancer is distinct in its latency and complexity, often manifesting years or decades after exposure. This delayed onset complicates diagnosis, treatment, and causality assessment [5]. Unlike infectious diseases or acute toxic exposures, the relationship between occupational exposure and cancer is multifactorial and depends on the nature, duration, intensity of exposure, and individual susceptibility. Furthermore, many occupational carcinogens are insidious, causing harm even at low doses over prolonged periods [6].

This review delves into the multidimensional scope of occupational medicine in addressing cancer toxicity. It explores the epidemiological burden of occupational cancer globally, identifies high-risk industries and carcinogenic agents, and discusses the mechanistic pathways through which occupational exposures induce malignancy including genotoxicity, oxidative stress, and epigenetic modifications. It also examines the role of biomarkers in early detection, outlines diagnostic and screening protocols, and evaluates current regulatory frameworks and compensation mechanisms designed to protect affected workers.

Moreover, the review highlights emerging challenges such as the rise of nanomaterials, gaps in data reporting, and the psychosocial impact of occupational cancer diagnoses. Finally, it proposes future directions, emphasizing the integration of digital surveillance, personalized occupational medicine, and global collaborations to enhance cancer prevention and care in occupational settings.
By adopting a comprehensive approach, occupational medicine can play a transformative role in reducing the burden of work-related cancers, improving early detection, and fostering safer workplaces across the globe.

2. Epidemiology of Occupational Cancer

Occupational cancer is a critical public health issue, accounting for a notable proportion of the global cancer burden. 843 000 work-related malignant neoplasms were reported in word wide in the year of 2019. In high-income, American, Eastern European and Western Pacific World Health Organization (WHO) regions, however, work-related malignant neoplasms comprised the biggest disease group [7]. This burden is often underestimated, especially in low- and middle-income countries where occupational health surveillance is limited. In high-income, industrialized nations, the risk may be even higher due to prolonged exposure to industrial carcinogens over decades. Despite advances in workplace safety, certain occupations still pose substantial cancer risks due to continuous exposure to harmful agents without adequate control measures [8].
Common occupational cancers include lung cancer, bladder cancer, mesothelioma, and certain skin cancers. Lung cancer is particularly prevalent among workers exposed to asbestos, silica, diesel exhaust, and metal fumes, all classified as Group 1 carcinogens by the International Agency for Research on Cancer (IARC). Mesothelioma, a rare but aggressive cancer of the pleura and peritoneum, is strongly linked to asbestos exposure, typically occurring decades after initial contact. Bladder cancer is often associated with exposure to aromatic amines, prevalent in the dye, textile, and rubber industries [9]. Non-melanoma skin cancers, including basal cell and squamous cell carcinoma, have also been linked to occupational exposure to substances like arsenic, coal tar, and ultraviolet radiation, particularly among outdoor workers [10].
Several industries are prominently associated with elevated occupational cancer risks. Asbestos mining and insulation work have long been known to increase the incidence of both mesothelioma and lung cancer. In the chemical manufacturing sector, substances such as benzene (linked to leukemia) and aromatic amines (associated with bladder cancer) pose significant health hazards [11]. The rubber industry has shown elevated rates of bladder and urinary tract cancers due to carcinogenic compounds used in the vulcanization process [9,12]. Workers in construction and shipbuilding are commonly exposed to asbestos, silica, and polycyclic aromatic hydrocarbons, all of which have carcinogenic potential. Similarly, in the textile and dye industry, prolonged contact with dyes and solvents containing aromatic amines significantly raises cancer risk [13].
Occupational exposures typically occur through inhalation, dermal absorption, or ingestion. Inhalation is the most frequent route, especially in environments with dust, fumes, and vapors. Dermal absorption is critical in cases where workers handle liquids or solids containing carcinogens without proper protective gear. Though less common, ingestion may occur indirectly when contaminated hands touch food or cigarettes. One of the major challenges in managing occupational cancers is the long latency period often 10 to 30 years between exposure and disease manifestation, complicating epidemiological tracking and delaying diagnosis and compensation [14]. Moreover, low-dose chronic exposures, often unrecognized by both employers and workers, can cumulatively lead to significant cancer risk.

3. Mechanisms of Occupational Cancer Toxicity

The development of occupational cancer is primarily driven by prolonged exposure to specific environmental and industrial carcinogens that interfere with normal cellular function and genetic stability. These substances induce carcinogenesis through several interconnected biological mechanisms, including genotoxicity, epigenetic alterations, oxidative stress, and chronic inflammation. Each of these pathways can disrupt cellular homeostasis, promote abnormal cell growth, and ultimately lead to the transformation of normal cells into malignant ones.

3.1 Carcinogenic Pathways

One of the most direct and well-established mechanisms is genotoxicity, where carcinogens interact with DNA, causing mutations, strand breaks, or chromosomal aberrations. Polycyclic aromatic hydrocarbons (PAHs), for example, found in coal tar, diesel exhaust, and grilled meats, can form DNA adducts that lead to permanent mutations during cell division. These mutations may activate oncogenes or inactivate tumor suppressor genes, initiating the carcinogenic process [15]. Figure 1 shows the different carcinogenic pathways involved in occupational cancer.

Epigenetic modifications represent a non-genotoxic route of cancer development. Carcinogens may alter the expression of key genes by influencing DNA methylation patterns, histone modifications, or microRNA expression, without changing the actual DNA sequence. This can silence tumor suppressor genes or activate oncogenes, contributing to unchecked cell proliferation [16].

Oxidative stress is another major contributor to occupational cancer. Many carcinogens stimulate the excessive production of reactive oxygen species (ROS), which can damage cellular lipids, proteins, and nucleic acids. This imbalance between ROS and antioxidant defenses results in DNA damage and genomic instability, promoting cancer initiation and progression [17].

Chronic inflammation, often triggered by long-term exposure to irritants such as asbestos or silica, also plays a crucial role in cancer development. Persistent inflammation can lead to continuous cell turnover, increased ROS production, and cytokine-mediated signaling, creating a microenvironment conducive to malignant transformation [18].

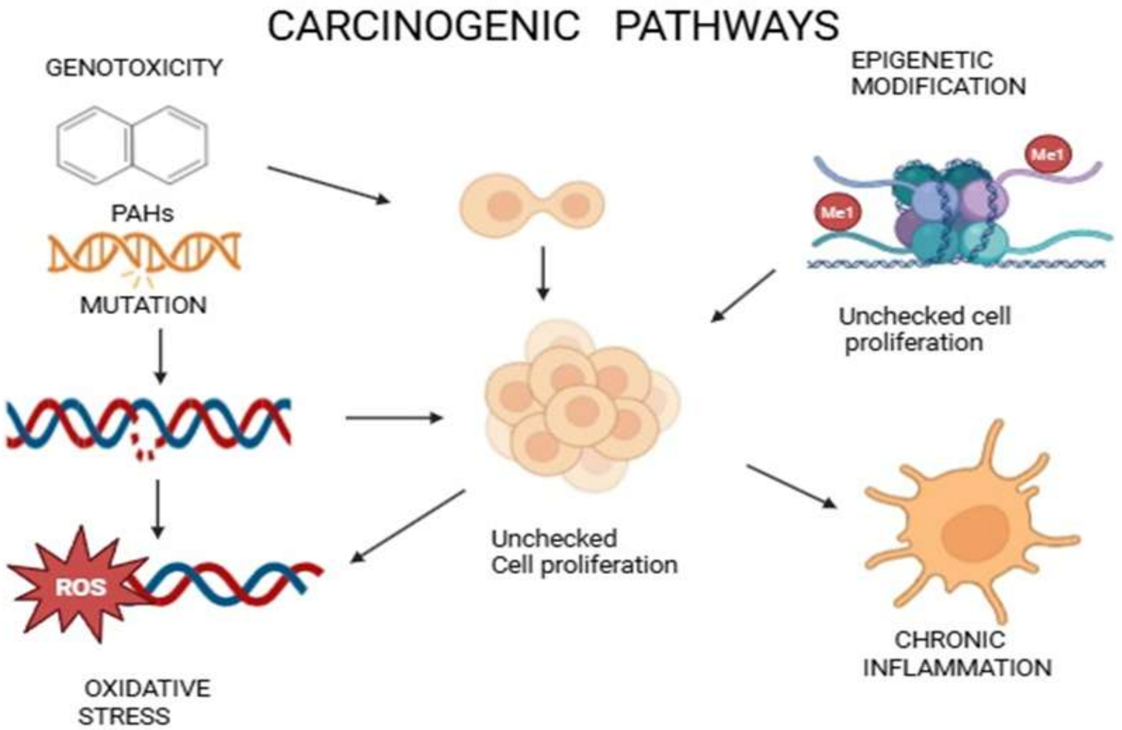

Figure 1. Carcinogenic pathways involved in cancer

3.2 Notable Occupational Carcinogens

Several occupational agents have been well-characterized in terms of their carcinogenic mechanisms and associated cancer types (Figure 2 and Table 1). For instance, benzene, a widely used industrial solvent, is known to cause hematopoietic DNA damage, leading to various forms of leukemia. Benzene metabolites can interfere with bone marrow function and induce chromosomal aberrations in hematopoietic stem cells [19].

Asbestos, long used in construction and insulation, causes mesothelial irritation, resulting in chronic inflammation and fibrosis that can progress to mesothelioma or lung cancer. Asbestos fibers physically disrupt cell membranes and induce oxidative stress, leading to DNA mutations [20].

Chromium VI compounds, used in electroplating and pigment industries, generate ROS that result in oxidative DNA damage, particularly in the nasal and lung tissues. These damages promote mutagenesis and carcinogenesis at the site of exposure [21]

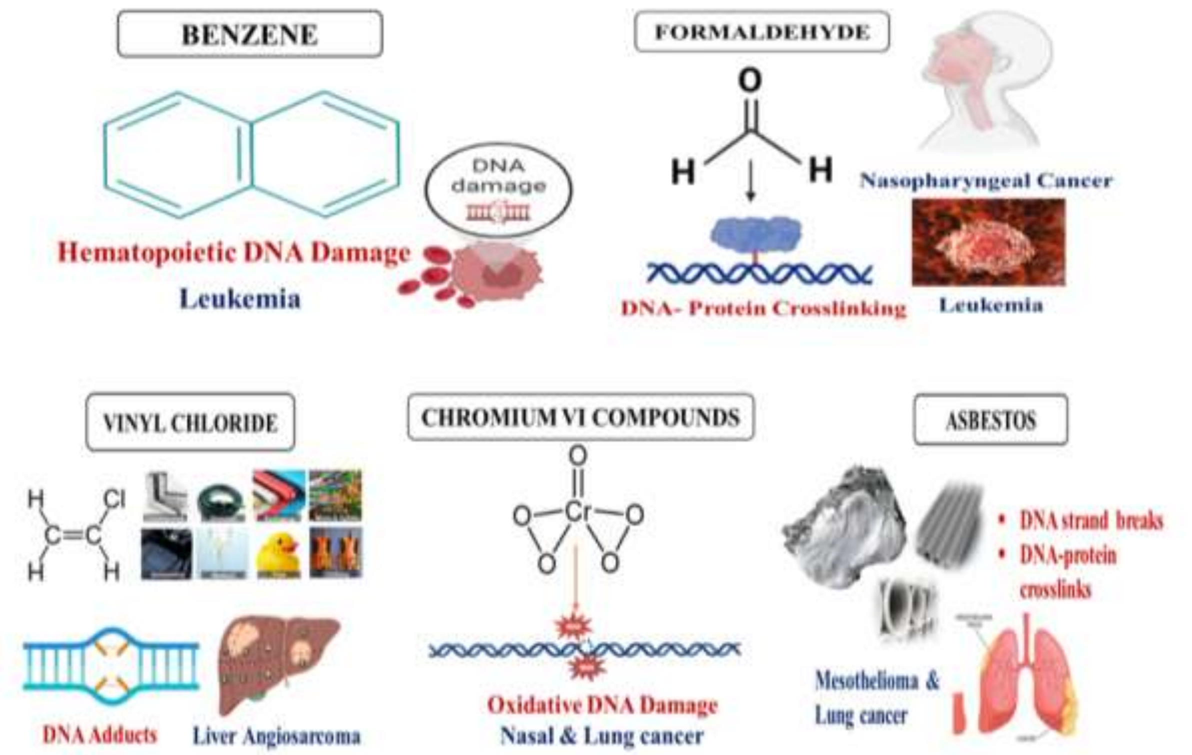

Figure 2. Notable occupational carcinogens

Vinyl chloride, used in plastic manufacturing, is metabolized in the liver to form reactive intermediates that form DNA adducts, a key mechanism in the development of liver angiosarcoma, a rare vascular tumor [22]
Lastly, formaldehyde, commonly found in laboratories and manufacturing industries, causes DNA-protein crosslinking, disrupting normal DNA replication and repair, and is strongly associated with nasopharyngeal cancer and leukemia [23].

Table 1: Key occupational carcinogens, exposure routes and associated cancers

Carcinogen	Source/Industry	Primary Exposure Route	Associated Cancer(s)	Mechanism of Toxicity
Asbestos	Construction, insulation, shipbuilding	Inhalation	Mesothelioma, Lung Cancer	Chronic inflammation, oxidative stress, cellular disruption
Benzene	Petrochemical, printing, rubber, solvents	Inhalation	Leukemia (AML), Bone marrow disorders	Hematopoietic DNA damage, chromosomal aberrations
Polycyclic Aromatic Hydrocarbons (PAHs)	Asphalt, coal tar, foundries, combustion	Inhalation, Dermal	Lung, Skin, Bladder Cancer	DNA adduct formation, genotoxic mutations
Aromatic Amines	Dye, textile, rubber industries	Dermal, Inhalation	Bladder Cancer	DNA mutations, metabolic activation
Chromium VI Compounds	Electroplating, pigments, welding	Inhalation, Dermal	Nasal, Lung Cancer	Oxidative DNA damage
Formaldehyde	Labs, wood products, textile finishing	Inhalation	Nasopharyngeal Cancer, Leukemia	DNA-protein crosslinking, repair inhibition

Vinyl Chloride	PVC manufacturing	Inhalation	Liver Angiosarcoma	DNA adduct formation, mutagenic metabolites
Silica Dust	Mining, construction, sandblasting	Inhalation	Lung Cancer, Silicosis	Chronic inflammation, fibrosis, ROS generation
UV Radiation	Outdoor occupations	Dermal	Non-melanoma Skin Cancer (BCC, SCC)	DNA photodamage, oxidative stress
Nanoparticles	Nanotechnology, electronics, materials	Inhalation	Potential Lung and Systemic Cancers (Emerging Evidence)	Poorly understood; inflammation, oxidative damage (hypothesized)

4. Diagnostic and Screening Strategies in Occupational Medicine

The early detection of occupational cancers is critical for improving prognosis and reducing mortality among exposed workers. Given the long latency period of many occupational cancers and the often-subtle onset of symptoms, a comprehensive and proactive diagnostic approach is essential. Occupational medicine employs a combination of biomarker analysis, health surveillance programs, and imaging and histopathological techniques to detect early signs of malignancy, assess exposure, and confirm diagnoses.

4.1 Biomarkers

Biomarkers are crucial tools in occupational cancer diagnostics as they provide early, measurable indicators of exposure, biological effect, or individual susceptibility. Exposure biomarkers detect the presence of carcinogenic substances or their metabolites in biological fluids. For example, urinary benzene metabolites such as trans,trans-muconic acid and S-phenylmercapturic acid are commonly used to assess benzene exposure in industrial workers. These indicators can help identify workers at risk even before clinical symptoms arise [24].

Effect biomarkers reflect early biological responses to carcinogen exposure and include DNA adducts, oxidative DNA lesions, and chromosomal aberrations. These changes may not be disease-specific but indicate molecular damage that could lead to cancer if persistent. For instance, DNA adduct formation caused by vinyl chloride or polycyclic aromatic hydrocarbons can signal a high cancer risk [25].

Susceptibility biomarkers identify individuals with genetic polymorphisms that alter their ability to metabolize or repair damage caused by carcinogens. Polymorphisms in genes such as CYP1A1, GSTM1, and NAT2 affect how efficiently a person detoxifies harmful compounds, influencing their vulnerability to occupational carcinogens [26]. Testing for these genetic variants can help stratify workers based on their risk and tailor preventive strategies accordingly.

4.2 Surveillance Programs

Occupational health surveillance programs are vital for the early detection and prevention of work-related cancers. These programs typically include pre-placement examinations to assess baseline health status and individual susceptibility, especially in genetically predisposed individuals. This step helps in identifying workers who may require more stringent protective measures or reassignment to safer environments.

Periodic medical evaluations are essential to monitor ongoing exposure effects and detect early signs of disease. These evaluations often involve clinical examinations, laboratory testing, and specific cancer screening protocols. For high-risk workers, such as smokers with asbestos exposure, low-dose computed tomography (CT) scans are recommended to screen for early lung cancer, significantly improving survival outcomes [27]. Female workers exposed to chemical agents may be included in routine Pap smear screening programs to detect cervical dysplasia or malignancy at early stages.

4.3 Imaging and Histopathology

Advanced imaging techniques such as positron emission tomography-computed tomography (PET-CT) and magnetic resonance imaging (MRI) are increasingly used for identifying and staging occupational cancers. These modalities provide detailed anatomical and metabolic information that enhances diagnostic accuracy [28]. Imaging is often supplemented by histopathological analysis of biopsy specimens, which remains the gold standard for confirming malignancy. Tissue samples are examined for cellular atypia, architectural disruption, and molecular markers, helping distinguish occupational cancers from sporadic ones. Importantly, all diagnostic efforts are contextualized by a thorough exposure history, which guides the selection of relevant tests and helps establish causality [29].

5. Regulatory Framework and Policy Measures

Addressing occupational cancer requires not only medical vigilance but also strong regulatory and policy interventions to minimize exposure to carcinogens in the workplace. Over the decades, various international organizations and national governments have established guidelines, regulations, and compensation mechanisms aimed at protecting workers from hazardous exposures. However, despite these efforts, significant gaps persist, especially in developing countries where regulatory enforcement remains weak.

5.1 International Agencies

Several global agencies play key roles in establishing and promoting occupational safety standards. The International Agency for Research on Cancer (IARC), a specialized agency of the World Health Organization (WHO), systematically evaluates the carcinogenic risks of various substances and classifies them into groups based on their carcinogenic potential. For instance, Group 1 agents are those confirmed to be carcinogenic to humans. This classification aids policymakers and occupational health authorities in identifying high-risk exposures and prioritizing regulatory action [30].

The Occupational Safety and Health Administration (OSHA), primarily in the United States, sets and enforces Permissible Exposure Limits (PELs) for toxic substances in the workplace. These limits are designed to protect workers from acute and chronic health effects, including cancer. OSHA also mandates hazard communication, training, and the use of protective equipment [31, 32]

The National Institute for Occupational Safety and Health (NIOSH) serves as a research-oriented body that conducts studies on occupational hazards and provides science-based recommendations to OSHA and employers. NIOSH's Recommended Exposure Limits (RELs) often serve as the basis for future regulations and inform best practices in occupational health management [33].

5.2 Legislation and Compensation

At the national level, countries implement specific legislation to manage occupational exposures and provide recourse for affected workers. In India, the Factories Act (1948) remains a cornerstone of occupational safety legislation. It mandates risk assessment, use of protective measures, and health monitoring in industrial settings. However, enforcement is often uneven, especially in smaller enterprises [34, 35].

The REACH Regulation (Registration, Evaluation, Authorisation and Restriction of Chemicals) in the European Union is a comprehensive legal framework for managing chemical safety. It requires manufacturers and importers to identify and manage risks associated with chemicals, including carcinogens, before they are marketed [36]. Most countries also have worker compensation schemes that offer financial support, rehabilitation, and medical coverage for individuals diagnosed with occupational cancers. These schemes typically require confirmation of both the cancer diagnosis and its link to occupational exposure, which can be challenging due to long latency periods and the need for detailed exposure histories.

5.3 Gaps in Regulation

Despite the existence of frameworks and policies, developing countries face major obstacles in effectively implementing occupational cancer control. Inadequate enforcement of existing laws often results in widespread exposure to known carcinogens. Moreover, many countries lack comprehensive occupational cancer registries, limiting the ability to track disease trends, plan interventions, or allocate resources effectively [37]. Another critical issue is the exclusion of informal sector workers, who often face the highest levels of exposure with the least protection and no access to legal recourse or healthcare benefits. This is particularly concerning in nations with large informal economies, where millions of workers remain vulnerable and unregulated [38]. To close these gaps, there is a pressing need for international collaboration, capacity-building in regulatory agencies, and the integration of occupational cancer into broader public health agendas.

6. Prevention Strategies in Occupational Medicine

Preventing occupational cancer is far more effective and cost-efficient than treating it after onset. The cornerstone of occupational cancer prevention lies in minimizing or eliminating workers' exposure to carcinogens through systematic control measures, education, and lifestyle interventions. Effective prevention strategies require a multi-level approach encompassing engineering, administrative, and personal controls, alongside efforts to promote safer industrial practices through green chemistry (Table 2).

6.1 Hierarchy of Controls

The hierarchy of controls is a globally accepted framework in occupational health for reducing exposure to workplace hazards. At the top of this hierarchy is elimination or substitution, the most effective intervention. This involves removing a carcinogenic agent from the work process or replacing it with a less harmful alternative.

For example, substituting benzene with a less toxic solvent significantly reduces the risk of hematopoietic cancers [39].
Next are engineering controls, which focus on isolating workers from hazards. Installing local exhaust ventilation systems, enclosed processes, or automated machinery reduces airborne exposure to carcinogens like silica dust, asbestos, and volatile organic compounds. These controls are particularly effective when used in high-exposure industries such as construction and chemical manufacturing [40].
Administrative controls aim to reduce the duration and frequency of exposure through policies such as job rotation, limiting work hours in high-risk zones, and scheduling hazardous tasks during times of minimal worker presence. These controls also involve maintaining exposure records and regular environmental monitoring [41].
Personal Protective Equipment (PPE) forms the last line of defense. PPE such as respirators, gloves, protective clothing, and eye protection are critical when higher-level controls are not feasible. However, PPE is often less effective than other methods because it relies on proper use and maintenance. Workers must be adequately trained and supervised to ensure PPE is used correctly [42].

6.2 Health Education and Training

Health education is essential for empowering workers to recognize hazards, adopt safe practices, and report early symptoms of exposure. Regular training sessions on chemical handling, emergency response, and safe disposal practices significantly lower the risk of accidental exposure. Employers must also educate workers about the importance of early reporting of health issues, which can lead to timely medical intervention and reduce long-term complications [43].

6.3 Lifestyle Interventions

Lifestyle modifications can mitigate the risk of developing occupational cancers, especially among high-risk populations. Smoking cessation is particularly critical, as tobacco smoke synergistically increases the carcinogenic effects of occupational exposures like asbestos and arsenic. Encouraging workers to adopt antioxidant-rich diets, which include fruits, vegetables, and whole grains, helps combat oxidative stress induced by carcinogen exposure [44]. Workplace wellness programs that support healthy behaviors can contribute significantly to reducing cancer incidence.

6.4 Green Chemistry Approaches

The long-term solution to occupational carcinogen exposure lies in rethinking the materials and processes used in industries. Green chemistry promotes the design and use of chemicals that are non-toxic or inherently safer. For instance, developing synthetic pathways that avoid carcinogenic intermediates or using biodegradable solvents can drastically reduce worker exposure and environmental contamination [45]. Many industries are now investing in safer alternatives and eco-friendly technologies, aligning with sustainability goals and regulatory requirements.

Table 2: Multilevel strategies for prevention and diagnosis of occupational cancer

Strategy Type	Specific Interventions	Target Outcome
Engineering Controls	Enclosed systems, exhaust ventilation, automation	Reduce airborne exposure to dusts, vapors, and fumes
Administrative Controls	Job rotation, exposure limits, shift scheduling, record-keeping	Minimize duration and frequency of exposure
Personal Protective Equipment (PPE)	Respirators, gloves, protective clothing	Personal barrier when other controls aren't feasible
Biomarkers	Benzene metabolites (urine), DNA adducts, gene polymorphisms (e.g., CYP1A1, GSTM1)	Early detection, exposure assessment, risk stratification
Health Surveillance	Pre-placement exams, periodic evaluations, cancer screenings (e.g., low-dose CT)	Monitor and detect disease early in high-risk groups
Worker Education	Hazard awareness, reporting symptoms, safe handling practices	Empower workers to prevent and recognize exposure
Green Chemistry	Substitution of toxic chemicals, eco-safe synthesis pathways	Eliminate hazard at source
Digital Monitoring	Wearable sensors, AI-based risk prediction	Real-time exposure control and predictive prevention
Global Policy & Regulation	IARC classification, OSHA/NIOSH guidelines, REACH legislation	Standardized control, compensation, and enforcement

7. Challenges and Emerging Issues

Despite significant advances in occupational medicine, the field continues to face numerous challenges in effectively preventing and managing occupational cancers. These obstacles span from the biological complexity of cancer development to systemic limitations in healthcare infrastructure, reporting, and emerging industrial risks. Addressing these issues requires a multifaceted approach that combines scientific insight with social and regulatory reforms.

7.1 Latency and Causation

One of the most persistent challenges is the long latency period associated with many occupational cancers. Diseases like mesothelioma or lung cancer may develop 20 to 40 years after initial exposure to carcinogens such as asbestos or silica. This delayed onset makes causal attribution particularly difficult, especially when workers have had multiple jobs or exposures over their lifetimes. Often, critical documentation on exposure levels, duration, and protective measures is unavailable or incomplete, hindering both diagnosis and compensation [46].

7.2 Underreporting

Another major issue is the underreporting of occupational cancers, particularly in low- and middle-income countries. Contributing factors include fragmented data systems, lack of trained occupational health professionals, and socioeconomic pressures that discourage workers from disclosing symptoms for fear of job loss or financial burden. Moreover, cancers often manifest after retirement, further detaching the illness from workplace exposure in the eyes of healthcare providers and insurance bodies [47]. This underreporting leads to a systematic underestimation of the true burden of occupational cancer, reducing political urgency for preventive action.

7.3 Nanoparticles and New Hazards

The rapid advancement of industries like nanotechnology has introduced a new class of potential occupational carcinogens. Nanoparticles, including carbon nanotubes and metal oxides, are increasingly used in electronics, medicine, and materials science. These particles can penetrate deep into lung tissue due to their ultra-small size, potentially inducing inflammation, fibrosis, and even tumor formation. However, the long-term carcinogenic potential of many engineered nanoparticles remains poorly understood, making regulation and protective measures challenging [48].

7.4 Psychosocial Aspects

Beyond physical health, a cancer diagnosis resulting from occupational exposure can have profound psychosocial consequences. Workers may face stigmatization, job loss, and financial instability, especially in informal employment settings. Additionally, the stress and trauma of cancer diagnosis often result in mental health deterioration, including anxiety, depression, and feelings of abandonment. Occupational health services must evolve to offer holistic care, including psychological counseling, reintegration support, and social services to mitigate the broader impact of occupational cancer [49].

8. Future Directions

To overcome these challenges and improve outcomes, occupational medicine must adopt innovative and inclusive strategies that align with technological progress and global health equity.

8.1 Digital Surveillance

The integration of digital technologies, including wearable sensors, Internet of Things (IoT) devices, and artificial intelligence (AI), can revolutionize exposure monitoring. Wearables can detect real-time environmental conditions such as gas concentrations, particulate matter, and noise, allowing for immediate alerts and timely interventions. AI algorithms can analyze trends and identify high-risk patterns, enabling predictive surveillance and personalized safety recommendations [50].

8.2 Personalized Occupational Medicine

The emerging field of personalized occupational medicine leverages genomic and proteomic profiling to identify individuals at increased susceptibility to certain carcinogens. For instance, workers with specific CYP450 or GSTM1 gene polymorphisms may benefit from enhanced screening or alternative work assignments. This approach not only improves early detection but also enables more targeted interventions, reducing the overall cancer burden [51].

8.3 Global Collaboration

Finally, addressing occupational cancer on a global scale requires robust international collaboration. Developing nations often lack the infrastructure, legislation, and expertise needed for effective occupational health management. Organizations like the World Health Organization (WHO) and International Labour Organization

(ILO) can play a central role in knowledge transfer, funding support, and capacity building. Joint initiatives can help standardize diagnostic criteria, improve surveillance, and develop universal guidelines for high-risk industries [52].

9. Conclusion

Occupational cancer represents a pressing global health issue that transcends medical, regulatory, and socioeconomic domains. Despite longstanding awareness of the links between workplace exposures and cancer, underreporting, weak enforcement of regulations, and insufficient worker protections persist, especially in low-resource settings. Occupational medicine, with its preventive foundation, holds the key to addressing these systemic gaps through early detection, risk assessment, and targeted interventions. The integration of modern diagnostic technologies, genomic profiling, and AI-driven exposure monitoring can transform cancer prevention efforts in occupational settings. However, these advancements must be supported by robust policies, international cooperation, and inclusive health services that reach informal and marginalized worker populations. To truly mitigate the burden of occupational cancer, a paradigm shift is required—one that prioritizes proactive health surveillance, environmentally safer industrial practices, and a global commitment to protecting workers' right to a healthy workplace.

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Conflicts of interest/Competing interests

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Reference

1. Klein AP. Pancreatic cancer epidemiology: understanding the role of lifestyle and inherited risk factors. Nature reviews Gastroenterology & hepatology. 2021 Jul;18(7):493-502.
2. Chika C. Occupational diseases and diseases associated with the workplace. International Journal of Medical Evaluation and Physical Report. 2021;5:1-3.
3. Iavicoli I, Spatari G, Chosewood LC, Schulte PA. Occupational medicine and Total Worker Health®: from preventing health and safety risks in the workplace to promoting health for the total well-being of the worker. La Medicina del Lavoro. 2022 Dec 7;113(6):e2022054.
4. Bang KM, editor. Modern occupational diseases diagnosis, epidemiology, management and prevention. Bentham Science Publishers; 2022 Sep 22.
5. Clapp RW, Jacobs MM, Loechler EL. Environmental and occupational causes of cancer: new evidence 2005-2007. Reviews on environmental health. 2008 Jan;23(1):1-38.
6. Hwai P, Lee T. Long-Term Imaging Surveillance of Radiation-Exposed Individuals: Insights from a Singaporean Population. Sriwijaya Journal of Radiology and Imaging Research. 2024;2(1):1-3.
7. Takala J, Hämäläinen P, Sauni R, Nygård CH, Gagliardi D, Neupane S. Global-, regional-and country-level estimates of the work-related burden of diseases and accidents in 2019. Scandinavian journal of work, environment & health. 2024 Feb 28;50(2):73.
8. Cumberbatch MG, Cox A, Teare D, Catto JW. Contemporary occupational carcinogen exposure and bladder cancer: a systematic review and meta-analysis. JAMA oncology. 2015 Dec 1;1(9):1282-90.
9. Kasperczyk E, Tarhonska K, Jablonska E. Genotoxicity Induced by Carcinogenic Agents or Occupational Exposure with Sufficient Evidence for Bladder Cancer. Journal of Clinical Medicine. 2025 Jun 25;14(13):4492.
10. Gbemudu BA. Environmental Risk Factors in Lung and Skin Cancer. Available at SSRN 4579295. 2023 Sep 21.
11. Seyyedsalehi MS, Bonetti M, Shah D, DeStefano V, Boffetta P. Occupational benzene exposure and risk of kidney and bladder cancers: a systematic review and meta-analysis. European Journal of Cancer Prevention. 2025 May 1;34(3):205-13.
12. Sorahan T. Bladder cancer risks in workers manufacturing chemicals for the rubber industry. Occupational medicine. 2008 Oct 1;58(7):496-501.
13. Uddin F. Environmental hazard in textile dyeing wastewater from local textile industry. Cellulose. 2021 Nov;28(17):10715-39.

14. Bang KM, editor. Modern occupational diseases diagnosis, epidemiology, management and prevention. Bentham Science Publishers; 2022 Sep 22.
15. Sankpal UT, Pius H, Khan M, Shukoor MI, Maliakal P, Lee CM, Abdelrahim M, Connelly SF, Basha R. Environmental factors in causing human cancers: emphasis on tumorigenesis. Tumor Biology. 2012 Oct;33(5):1265-74.
16. Szczepanek J, Skorupa M, Jarkiewicz-Tretyn J, Cybulski C, Tretyn A. Harnessing epigenetics for breast cancer therapy: the role of DNA methylation, histone modifications, and MicroRNA. International journal of molecular sciences. 2023 Apr 13;24(8):7235.
17. Zhao Y, Ye X, Xiong Z, Ihsan A, Ares I, Martínez M, Lopez-Torres B, Martínez-Larrañaga MR, Anadón A, Wang X, Martínez MA. Cancer metabolism: the role of ROS in DNA damage and induction of apoptosis in cancer cells. Metabolites. 2023 Jun 27;13(7):796.
18. Herb M, Schatz V, Hadrian K, Hos D, Holoborodko B, Jantsch J, Brigo N. Macrophage variants in laboratory research: most are well done, but some are RAW. Frontiers in Cellular and Infection Microbiology. 2024 Oct 9;14:1457323.
19. Yusoff NA, Abd Hamid Z, Budin SB, Taib IS. Linking benzene, in utero carcinogenicity and fetal hematopoietic stem cell niches: a mechanistic review. International Journal of Molecular Sciences. 2023 Mar 28;24(7):6335.
20. Visonà SD. Asbestos exposure and malignant mesothelioma: the role of inorganic fiber burden and disruption of iron homeostasis in lung microenvironment. A postmortem study on human lungs.
21. Singh V, Singh N, Verma M, Kamal R, Tiwari R, Sanjay Chivate M, Rai SN, Kumar A, Singh A, Singh MP, Vamanu E. Hexavalent-chromium-induced oxidative stress and the protective role of antioxidants against cellular toxicity. Antioxidants. 2022 Nov 30;11(12):2375.
22. Guardiola JJ, Hardesty JE, Beier JI, Prough RA, McClain CJ, Cave MC. Plasma metabolomics analysis of polyvinyl chloride workers identifies altered processes and candidate biomarkers for hepatic hemangiosarcoma and its development. International Journal of Molecular Sciences. 2021 May 11;22(10):5093.
23. Ladeira C, Viegas S. Formaldehyde: exposure and genotoxicity assessments and potential health effects. SYNTHESIS, APPLICATIONS AND POTENTIAL HEALTH EFFECTS. 2015:61.
24. Rahimpoor R, Jalilian H, Mohammadi H, Rahmani A. Biological exposure indices of occupational exposure to benzene: A systematic review. Heliyon. 2023 Nov 1;9(11).
25. Alifia NA, Tualeka AR. Effect Vinyl Chloride to DNA Methylation: A Systematic Review. Media Gizi Kesmas. 2023;12(2):1095-106.
26. Gajecka M, Rydzanicz M, Jaskula-Sztul R, Kujawski M, Szyfter W, Szyfter K. CYP1A1, CYP2D6, CYP2E1, NAT2, GSTM1 and GSTT1 polymorphisms or their combinations are associated with the increased risk of the laryngeal squamous cell carcinoma. Mutation Research/Fundamental and Molecular Mechanisms of Mutagenesis. 2005 Jul 1;574(1-2):112-23.
27. Maisonneuve P, Rampinelli C, Bertolotti R, Misotti A, Lococo F, Casiraghi M, Spaggiari L, Bellomi M, Novellis P, Solinas M, Dieci E. Low-dose computed tomography screening for lung cancer in people with workplace exposure to asbestos. Lung Cancer. 2019 May 1;131:23-30.
28. Owens CA, Hindocha SU, Lee RI, Millard TH, Sharma BH. The lung cancers: staging and response, CT, 18F-FDG PET/CT, MRI, DWI: review and new perspectives. The British Journal of Radiology. 2023 Jul 1;96(1148):20220339.
29. Prajapati VD, Ferreir JL, Patil K. Heart cancer: Biomarker landscape. InBiomarker Landscape in Cancer Research 2025 Jan 1 (pp. 41-73). Academic Press.
30. Turner MC, Cogliano V, Guyton K, Madia F, Straif K, Ward EM, Schubauer-Berigan MK. Research recommendations for selected IARC-classified agents: impact and lessons learned. Environmental Health Perspectives. 2023 Oct 30;131(10):105001.
31. Finkel AM, Johns DO, Whittaker C. Occupational Risk Assessment. InRisk Assessment for Environmental Health 2022 Dec 30 (pp. 225-265). CRC Press.
32. Howard J, Smith S. Occupational Safety and Health Law. Patty's Industrial Hygiene, Volume 2: Evaluation and Control. 2021 Apr 1:307.
33. Kasangaki MW, Scholar PG. OCCUPATIONAL TOXICOLOGY. Principles of Medical Toxicology. 2025 Jun 10:336.
34. Anand R. Rebuilding Safety: lessons from India's top 10 industrial Catastrophes. Anand; 2024 Oct 14.
35. Khurram M, Zhang C, Muhammad S, Kishnani H, An K, Abeywardena K, Chadha U, Behdinan K. Artificial Intelligence in Manufacturing Industry Worker Safety: A New Paradigm for Hazard Prevention and Mitigation. Processes. 2025 May 1;13(5).

36. Gebel T, Lechtenberg-Auffarth E, Guhe C. About hazard and risk assessment: Regulatory approaches in assessing safety in the European Union chemicals legislation. Reproductive Toxicology. 2009 Sep 1;28(2):188-95.
37. World Health Organization. Cancer control: knowledge into action: WHO guide for effective programmes. World Health Organization; 2007.
38. Mbengi RK, Tiraboschi M, De Brouwer C, Bouland C. How do social security schemes and labor market policies support the return-to-work of cancer survivors? A review article. Journal of cancer policy. 2018 May 1;15:128-33.
39. Chawla M. Environmental contamination and toxicology of benzene-hexachloride (BHC). InHazardous Chemicals 2025 Jan 1 (pp. 85-103). Academic Press.
40. Kubba S. Indoor environmental quality (IEQ). LEED v4 Practices, Certification, and Accreditation Handbook. 2015 Dec 4:303.
41. Burton K, Johnstone K. Control Strategies for Workplace Health Hazards. InPrinciples of Occupational Health and Hygiene 2024 Nov 5 (pp. 90-105). CRC Press.
42. Ludy S, Eyre AJ. Personal Protective Equipment. InCiottone's Disaster Medicine 2024 Jan 1 (pp. 323-329). Elsevier.
43. Alfano CM, Leach CR, Smith TG, Miller KD, Alcaraz KI, Cannady RS, Wender RC, Brawley OW. Equitably improving outcomes for cancer survivors and supporting caregivers: a blueprint for care delivery, research, education, and policy. CA: a cancer journal for clinicians. 2019 Jan;69(1):35-49.
44. Holen S. How To Prevent and Reverse Cancer Naturally: Strategies to defeat cancer without Chemotherapy, Beat breast, and prostate colon cancers, Starve cancer cells with diet, and lifestyle changes, recipes, diet and smoothies. Sam Holen; 2023 Aug 10.
45. Jha A, Jha M. The Hidden Dangers: How Synthetic Organic Compounds Impact Health and the Environment. International Journal of Nursing Information. 2024 Dec 31;3(2):9-21.
46. Demers PA. Using Scientific Evidence Principles to Help Determine the Work-Relatedness of Cancer. Toronto, ON: Occupational Cancer Research Centre, Ontario Health. 2020 Jan 9.
47. Rondinone BM, Fontana L, Buresti G, Fedele M, Fortuna G, Iavicoli S, Lecce MG, Persechino B. The challenges of managing patients with cancer in the workplace: Needs, opportunities and perspectives of occupational physicians. PloS one. 2023 Jul 27;18(7):e0288739.
48. Ahmad A, Imran M, Sharma N. Precision nanotoxicology in drug development: current trends and challenges in safety and toxicity implications of customized multifunctional nanocarriers for drug-delivery applications. Pharmaceutics. 2022 Nov 15;14(11):2463.
49. Jain A, Hassard J, Leka S, Di Tecco C, Iavicoli S. The role of occupational health services in psychosocial risk management and the promotion of mental health and well-being at work. International journal of environmental research and public health. 2021 Mar 31;18(7):3632.
50. Ozobu CO, Adikwu FE, Cynthia OO, Onyeke FO, Nwulu EO. Developing an AI-powered occupational health surveillance system for real-time detection and management of workplace health hazards. World Journal of Innovation and Modern Technology. 2025;9(1):156-85.
51. Narendra G, Choudhary S, Raju B, Verma H, Silakari O. Role of genetic polymorphisms in drug-metabolizing enzyme-mediated toxicity and pharmacokinetic resistance to anti-cancer agents: a review on the pharmacogenomics aspect. Clinical Pharmacokinetics. 2022 Nov;61(11):1495-517.
52. Adikwu FE, Ozobu CO, Odujobi O, Onyeke FO, Nwulu EO. A Comprehensive Review of Health Risk Assessments (HRAs) and Their Impact on Occupational Health Programs in Large-Scale Manufacturing Plants.