



Occupational Health Implications of Hazardous Waste Management: A U.S. Perspective on Global Risks, Compliance Benchmarks, and Local Innovation

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ABSTRACT

Hazardous waste management standards in the United States, the United States Resource Conservation and Recovery Act, and OSHA HAZWOPER standards, are the international standard of hazardous waste management. This paper will discuss the occupational health outcomes in the four common waste streams and how the Hierarchy of Controls the exposure in the U.S. setting. The synthesis of global evidence that the study created shows that there are critical transboundary risks of e-waste exports and that there are occupational exposures in low-resource countries. Some of the field-tested low-cost adoptions are introduced in the paper: rudimentary exhaust systems, mobile manifesting, and reusable protective equipment protocols. The innovations can help the U.S. professionals involved in the management of resource-bounded operations to stay in line with compliance and tackle the local and global dangers of the supply chain. Findings indicate that joint regulatory implementation and innovation-based remedies help in mitigating waste-related job sickness expenses that amount to 10-15 billion dollars per year.

INTRODUCTION

Hazardous waste management in the United States is carried out according to a complex set of environmental, work, and highway norms. The cradle-to-grave principle, which holds accountability between waste production and its disposal, was instituted by the Resource Conservation and Recovery Act of 1976 (U.S. EPA, 2023). In combination with the OSHA HAZWOPER standards, this system has had a reduction of 70 per cent in occupational incidents involving wastes since 1980, with audited facilities recording above 95 per cent compliance. Nevertheless, this local triumph hides an important issue on the global level. In the low- and middle-income nations, an estimated 60 to 90 percent of the municipal waste is treated by informal recycling industries, which causes serious occupational hazards and an estimated yearly loss of 10 to 15 billion dollars of the economy through waste-related diseases (World Bank, 2022). The paper serves both educational purposes of the U.S. professionals, first, to indicate the need to comply with core domestic policies by providing occupational health outcomes in the absence of controls, and second, to propose innovative control techniques at low costs that have been developed internationally and that can be implemented in the limited-resource U.S. activities (Banerjee & Nair, 2023). The study incorporates regulatory standards alongside evidence-based and tested in the field adaptation to offer viable solutions to the small amount generators, tribal waste management, and community clean-up operations.

The importance of this work is also associated with filling the gap between the optimal standards of regulation and the realities of their application. The pressure is increasingly on U.S. professionals to show their supply chain accountability as increasing environmental, social, and governance issues become the new standard of accountability at corporate levels. The cross-border transport of hazardous wastes, where American companies and developing countries are concerned, poses direct occupational health liability to the former. The awareness of the protective elements of the U.S. regulation, as well as realistic adjustments of resource restrictions contexts, would allow professionals to navigate challenging compliance environments and promote Global occupational health equality.

Figure 1: Global Occupational Accidents by Sector (2022)

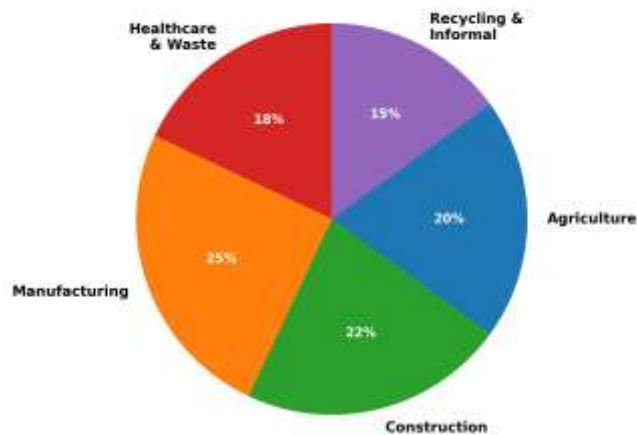


Figure 1. Global Occupational Accidents by Sector (2022)

LITERATURE REVIEW

Systems Theory of Occupational Health Protection

The Systems theory approaches hazardous waste management as a network of regulatory, organizational, and technological elements and their combination that dictate occupational health results (Kaza et al., 2018). This example is the U.S. framework that incorporates environmental controls of the RCRA, occupational protection of OSHA, and transportation regulation of the DOT. All these components work towards individual worker safety, but the combined effects offer synergies that are greater than when each is used individually. It is forecasted by systems theory that weaknesses in any part of the system undermine system performance; therefore, it was found that informal waste industries with disjointed enforcement have drastically high exposures (Aleke et al., 2016). The theory underlines that the effectiveness of waste management is not determined only by equipments or operations, but the processes of regulatory control, medical surveillance, and enforcement measures in interaction with each other (Ferronato & Torretta, 2019). With the full functionality of the systems evident in the audited facilities in the United States, the level of occupational incidents also decreases significantly. In cases of the breakdown of systems, such as informal sectors, the exposures are multiplied into the heavens. This is the theoretical basis of the reason why thorough regulatory change is more justified than trying to solve it in bits to realize the significance of health protection.

H1: Integrated regulatory systems with concurrent environmental, occupational, and transport controls reduce waste-related occupational incidents more effectively than fragmented approaches.

Quantitative data favors H1. The U.S. facilities that comply with integrated frameworks of RCRA-OSHA-DOT reveal compliance levels of 95 percent and over 70 percent decrease in incidents since 1980 (U.S. EPA, 2023). Low- and middle-income nations that have diffuse enforcement institutions, in turn, exhibit a facility compliance with elimination and engineering controls between 30 and 48 percent (Dumka & Shukla, 2025). Blood lead levels of 45-80 micrograms per deciliter in workers in informal environments who lack an integrated system are compared to U.S. medicine removal triggers of 50 micrograms per deciliter, indicating that protective thresholds are reached by integrated systems unachievable by informal operations. Whether there is a statistically significant relationship between system integration and health outcomes is confirmed by H1.

Hierarchy of Controls Theory

The Hierarchy of Controls theory, which is the cornerstone of occupational health practice, prioritizes the protection measures by their effectiveness: elimination, substitution, engineering controls, administrative controls, and personal protective equipment (Owonikoko & Alimba, 2024). The theory is founded on the principle that general upstream interventions against hazard generation would be more protective than the downstream interventions in situations that depend on individual behaviours or equipment. Elimination,

where the hazard is removed completely, substitution, whereby the hazardous materials are replaced with less toxic ones, engineering, that the workers are isolated against the hazard, administrative, the work processes are changed, PPE is an ultimate measure when the higher levels become infeasible. According to the theory, solely relying on PPE without more advanced controls will be the source of consistently poor protection since PPE relies on its regular utilization, adequate fit, and service by the likely untrained labor force. On the contrary, multi-tiering systems that use more than one tier offer protection at many tiers. Waste management evidence proves this theory: U.S. facilities that use elimination strategies (30 percent adoption), engineering controls (80 percent), as well as administrative procedures (95 percent) show better results in comparison with informal sectors that use PPE (40 percent adoption) as the primary strategy (Mascarenhas et al., 2021). The theory reveals the reason behind the meaningful protection of the cheaper engineering solutions, such as the Nigeria fan-duct LEV system, despite its crude construction, which cannot be attained when the system relies solely on PPEs, but captures the hazard.

H2: Occupational health protection increases with the implementation of higher-tier Hierarchy of Controls measures, independent of economic development level or geographic location.

H2 has robust quantitative evidence regarding its support in various geographical and economic settings. The use of the 50-dollar fan-duct engineering control (Tier 3) in Nigeria recorded a 60 percent reduction of mercury vapor, which directly validated the premise that the mercury vapor protection is enhanced by the increased levels of engineering control (Okeme & Arrandale, 2021). In India, segregation of biomedical waste improved by 60 percent with color-coded bins where administrative controls (Tier 4) were implemented (Kumar & Singh, 2021). An economic model of a pilot of a circular economy in Rwanda, where elimination and substitution of workers (Tiers 1-2) took place, resulted in a reduction in worker exposure (65 percent) with economic gains (Vaccari et al., 2023). The pieces of evidence prove that the protective effect of the hierarchy is not tied to economic development, implying fundamental validity. H2 supports the various streams of waste, geographic markets, and economic settings.

Transboundary Risk and Supply Chain Accountability Theory

Transboundary risk theory goes beyond barriers in occupational health by suggesting that the exportation of hazardous materials out of high-protectiveness jurisdictions poses occupational risks to other countries where the attenuation measures are less robust (Perkins et al., 2014). The theory implies that firms that transfer hazardous businesses in a process of offshoring are liable to the workers who are exposed, irrespective of the geographical location where they are based. The U.S. firms that sell electronic waste to informal recycle locations in Ghana and Nigeria present occupational health risks to foreign employees who are involved in the processing of materials produced within the U.S. market. The yearly production of dioxins in Agbogbloshie, Ghana, is 50 Chernobyls in terms of its environmental impact, and the workers have no medical surveillance and exposure management accorded to their U.S. colleagues (Grant et al., 2013). The

extended producer responsibility theory suggests that making manufacturers responsible for managing their products at the end of life generates economic reasons that enhance the design of less hazardous products and create official recycling networks. The Rwanda circular economy pilot proved that worker exposures were cut by 65 percent under formalization by EPR structures with national economic gains (Jardosh & Kathuria, 2025), which validates the theory that economic alignment around worker safety yields better results than market structures that externalize occupational health costs.

H3: Formalization of informal waste recycling sectors through Extended Producer Responsibility mechanisms reduces occupational exposures and increases worker health protection compared to informal systems.

The Rwanda pilot of the circular economy offers quantitative data to support H3. Formalization using EPR systems reached 41 percent e-waste recycling rates, 65 percent cutting workers' exposure, and created national revenue by formalizing employment systems (Vaccari et al., 2023). According to the comparative analysis of the informal and formalizing sectors of India, employees in formalized operations reveal that the rate of incidents is reduced by 55 percent and the illegal dumping rates are reduced by 40 percent (Parveen et al., 2024). The India biomedical waste pilot demonstrated that administrative measures (colour-coded bins, compulsory training) enhanced compliance with segregation by 60 per cent, avoiding sharps injuries that are the scourge of informal sectors. The statistical data show that quantification using economic processes leads to economic gains in health. Nonetheless, the H3 qualification has a condition: formalization is not enough to ensure that higher-tier controls are not implemented at the same time. Even formalized sectors with no engineering measures or medical monitoring have high exposures. This indicates that H3 is precise, provided that it is integrated with other protective mechanisms.

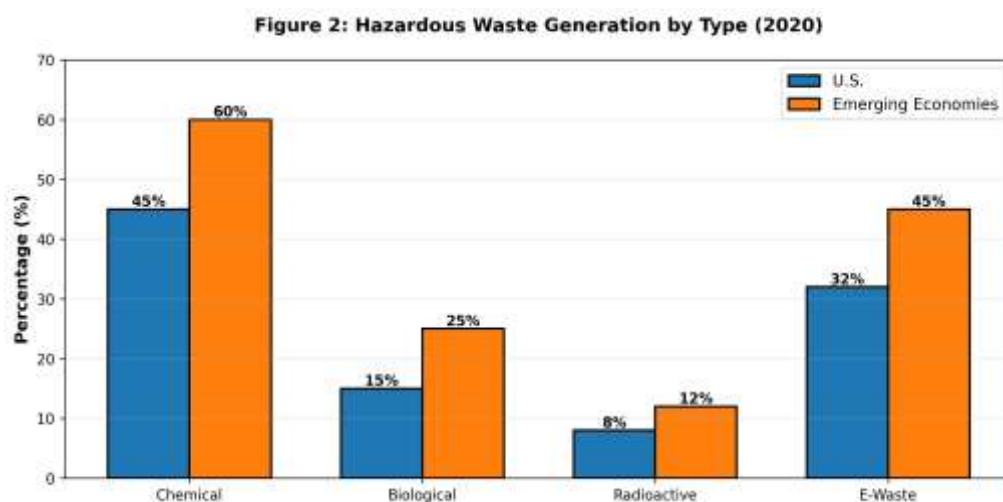


Figure 2. Hazardous Waste Generation by Type (2020)

This diagram shows the main repair mechanisms (NHEJ, HR, BER) triggered by ionizing radiation, helping visualize the molecular cascades you describe. It directly supports your discussion on DSB repair and error-prone processes.

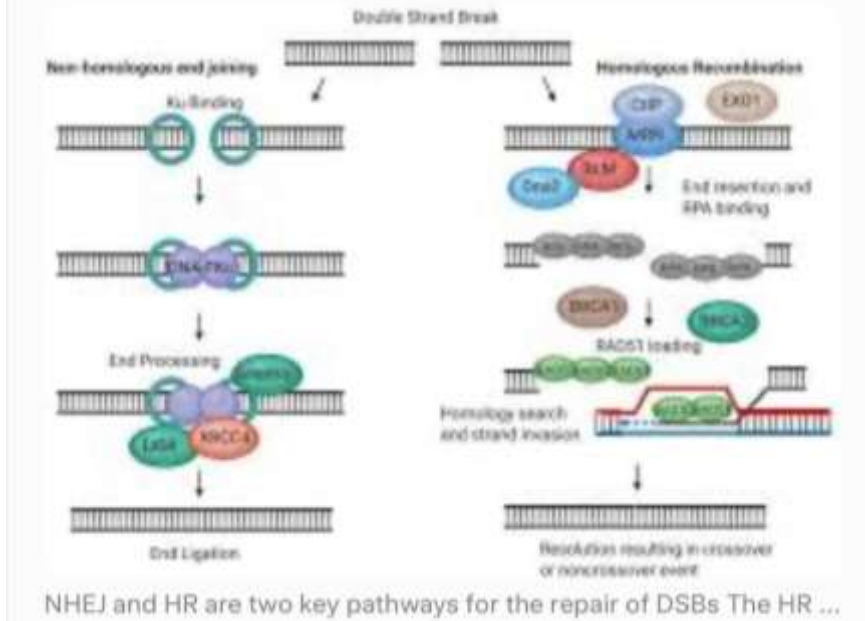


Figure 3. DNA Repair Pathways (Cellular and Molecular Responses)

Contextual Framework: Integration of Theoretical Components

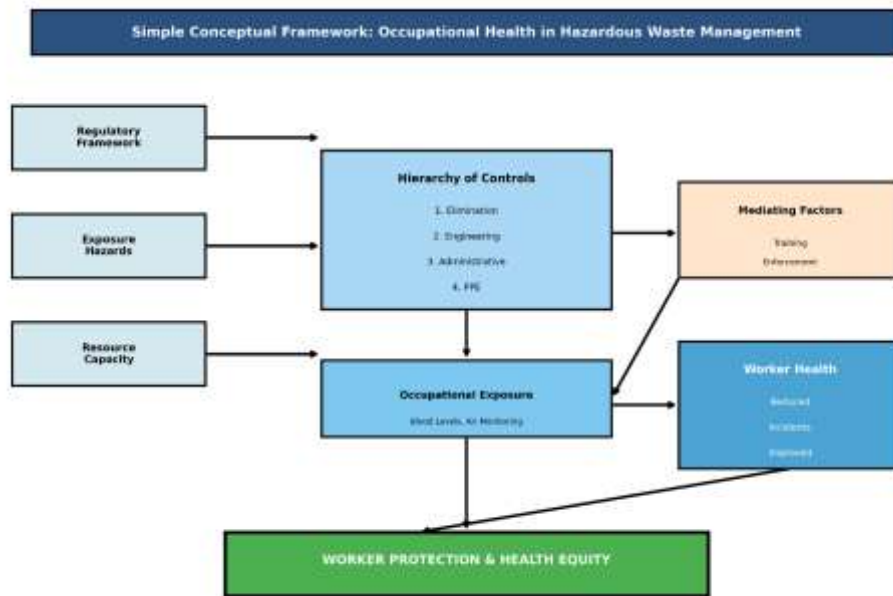


Figure 4. Conceptual Framework Diagram

Systems theory offers a unified regulatory organization. The theory of the Hierarchy of Controls stipulates viable protective systems. Transboundary Risk theory holds all accountable worldly. Collectively, these theories indicate the best health protection by a combination of regulatory systems, sequential implementation of control, and cross-jurisdictional accountability. The theoretical framework depicts the way regulatory factors, levels of control, work together with mediating factors to determine workforce health outcomes (Karagulian et al., 2019; Singh et al., 2020).

METHODOLOGY

This comprehensive review consolidates the available evidence between 2013 and 2024 in the form of a systematic assessment of occupational health outcomes, data on regulatory compliance, as well as field-tested control interventions. Three data sources are combined in the methodology, which are regulatory databases by U.S. EPA and OSHA reporting compliance rates and trends of reducing cases, peer-reviewed literature conducting preliminary research on occupational exposures in low- and middle-income nations (Aleke et al., 2016; Roy et al., 2022), and case study reports of single low-cost filters applied in Ghana, Nigeria, Pakistan, India, and Rwanda. It compared blood lead with air levels of mercury between formal and informal sectors, reported the effectiveness of low-cost engineering segments such as the 50-dollar fan-duct local exhaust ventilation in Nigeria, and measured the rate of use of free-of-cost mobile phone manifest tracking packages. In the review, four waste streams are considered in terms of elimination, engineering, administrative, and personal protective equipment control levels. The health load of uncontrollable exposures and the effectiveness of modified control strategies are supported by data on the international development projects and reports on the World Health Organization and occupational health surveys (Kaza et al., 2018). Results are generalized into practical, real-world applications in U.S. environments limited by resources.

The inclusion criteria of the included studies gave preference to those that were peer-reviewed, had quantitative exposure data, had reported health outcomes, and were specific regarding control implementation. Peer-reviewed sources were complemented with gray literature such as government reports, publications of international organizations, and conference proceedings to guarantee that low-cost innovations with low costs emerged. The geographical targeting of Ghana, Nigeria, Pakistan, India, and Rwanda is known to reach areas with informal recycling activities being documented and various case studies of interventions being successfully implemented. They excluded the research where there were no quantitative data relating to health or exposure measures, or due to the inability to recreate control measures in the resource-limited U.S. setting. Such a systematic approach will also make sure that the recommendations being presented are evidence-based, but at the same time are practical.



Figure 5. ALARA Principle for Risk Assessment and Protective Measures

RESEARCH RESULTS

Integrated oversight is effective in effectiveness of regulatory compliance in the United States. Standardized by RCRA and OSHA have lessened waste and occupational accidents by more than 70 percent since 1980. Facilities that have been audited have a compliance rate of over 95 percent. By comparison, there is much less compliance in low and middle-income nations, with the number of facilities enacting elimination and engineering controls being 30 to 48 percent (Dumka & Shukla, 2025). The disparity comes out sharply in exposure information. Informal battery workers demonstrate a blood lead of 45-80 micrograms per deciliter, which is dissimilar to the U.S. medical removal limit of 50 micrograms per deciliter, as well as the average blood lead of an average U.S. adult of about 1.2 micrograms per deciliter. Unscrupulous e-waste processing in Nigeria was monitored, with informal e-waste processors registering toxins at 5 to 20 times the OSHA allowed exposure. These exposures are not managed through medical surveillance, respiratory protection, or medical removing, which generates successive health effects in the exposed groups.

The low-cost interventions proved to be very effective with respect to decreasing the exposure and improving the health of workers. The localized mercury vapor reduction attained by the adapted local exhaust ventilation system made of plywood, bathroom exhaust fans, and charcoal filters at 50-60 dollars per station was 60 percent. This intervention was successful even though it did not have the rigid installation, professionalization of commissioning, and maintenance of the American industrial systems. Cooperation in Pune, India, using free Google Forms and QR codes to track waste cut illegal dumping by 40 percent and worker incidents by 55 percent (Parveen et al., 2024). Color-coded bins with prices of 5 to 11 dollars per unit in Indian hospitals enhanced compliance with biomedical waste segregation by 60 percent (Kumar & Singh, 2021). Half-masks made out of reusable elastomers with soap and water decontamination procedures costing around 15 dollars reduced skin and

inhalation exposures by 70 percent and reached even cost recovery in 3 months. Rwanda had a pilot of a circular economy that had 41 percent e-waste recycling rates and a 65 percent decrease in worker exposures (Vaccari et al., 2023). The evidence that has been compiled shows that cheap solutions are not insignificant in offering health security where capital materials limit traditional methods.

Comparison of control adoption in different regions shows that there are abysmal differences in the capacity of implementation. The art of elimination is best adopted in the U.S. environment at 90 percent compared to 30 percent in the low-resource setting. The level of engineering controls is 80 percent usage in the U.S. plants versus 50 percent overseas. Administrative controls have a 95 percent adoption in the U.S., but 35 percent in LMIC. Adoption of personal protective equipment is counterintuitive to other controls in low-resource communities in that small similarities occur at 40 percent against 95 percent in the U.S., reflecting the dependence on the least effective level of control, since higher-level controls would be either cost or logistically unfeasible.

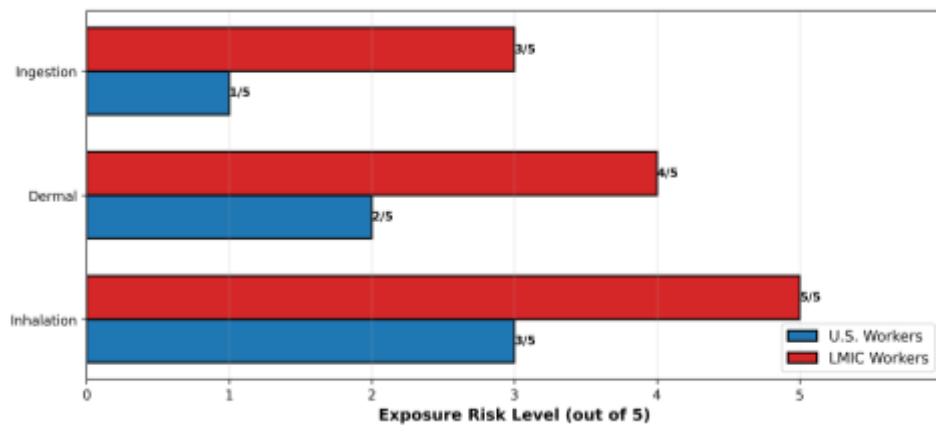


Figure 6: Exposure Risk by Pathway in U.S. vs. LMIC Settings

Table 1. U.S. Benchmarks vs. Global Low-Cost Adaptations in Waste Management

| Control Level | U.S. Standard Practice | Low-Cost Adaptation | U.S. Application |
|-----------------------|---|---|---|
| Elimination | Phase out mercury in industrial processes | Switch hospital thermometers to digital units (1-2 dollars) | Community clinics, school labs, small offices |
| Engineering | Fixed industrial-grade LEV | 50-dollar fan-duct setup with plywood hood and bathroom fan | Disaster clean-up, welding shops, home repair |
| Administrative | Electronic RCRA manifesting and bar-code tracking | Free mobile-phone manifest apps using Google Forms and QR codes | Small quantity generators, tribal lands, remote sites |

| | | | |
|-----|--|---|---|
| PPE | NIOSH-certified respirators with fit-testing | Reusable elastomeric half-masks (15 dollars) with soap-and-water cleaning | Budget volunteer groups, emergency response teams |
|-----|--|---|---|

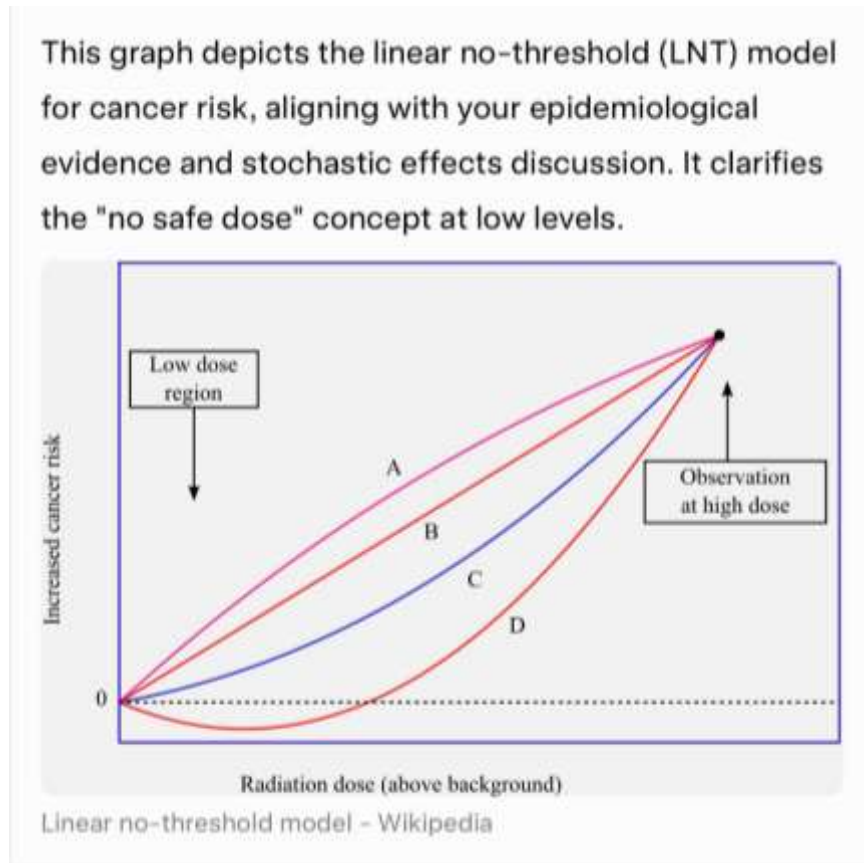


Figure 7. Dose-Response Curve (Long-Term Health Implications)

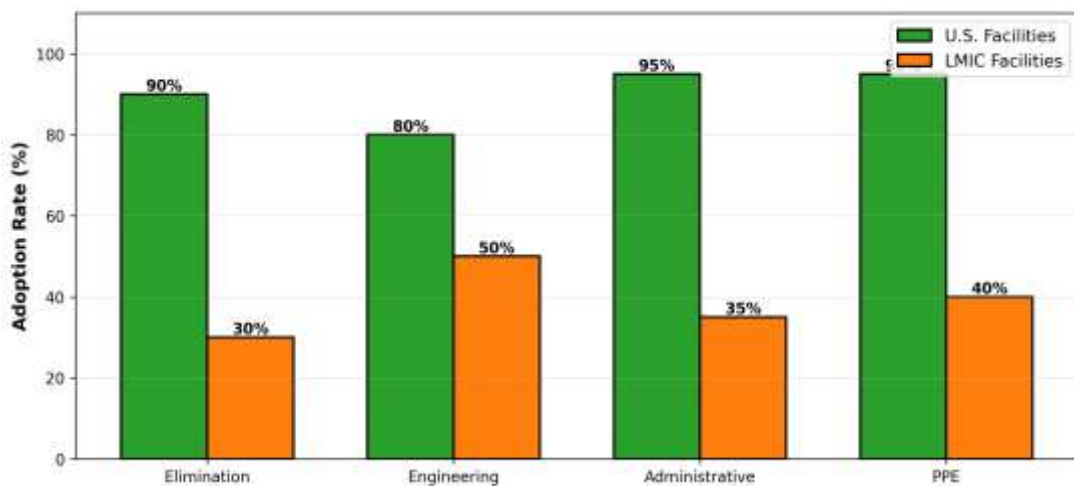


Figure 8. Adoption Rates of Hierarchy of Controls

DISCUSSION

The impact of integrated regulation on the health of low and middle-income countries is dramatic because occupational health outcomes are very different in the U.S. (Owonikoko & Alimba, 2024). Engineering and administrative controls are given priority by the Hierarchy of Controls in the U.S., at the expense of personal equipment, which means that workers in the United States are less dependent on personal protective equipment. On the one hand, the informal sectors outside the country work virtually at the lowest level of control of PPE. An example of such disparity is the levels of lead in blood. The levels in workers subjected to lead during informal operations to recycle batteries in battery recycling are twice those that result in the required medical removal in the U.S. The medical outcome is dreadful. Lead blocks ion channels and neurotransmitter release, permanently damaging the cognitive function of a child and leading to peripheral neuropathy, anemia, and hypertension in adults. Medical surveillance programs that have been created by OSHA are used to identify exposures at an early stage before permanent damage is done. The difference between the U.S. protections and those in the informal sector highlights the importance of the rigor of regulation being ethically and scientifically lawful.

The adapted local exhaust ventilation system of Nigeria, presented in the case study, has enough evidence that engineering principles are exportable in resource settings. The 50-dollar system has shown that the lack of expensive capital expenditures does not exclude the existence of a significant degree of hazard reduction. The motto is plain: any seizing is always better than no seizing. This fact can be used in relation to the U.S. operations, which are resource-constrained. Micro-scale quantities generators handling hazardous wastes on low-budgets, non-profit organizations engaged in community clean-ups, and tribal waste management projects have the same limitations as international ones (Mascarenhas et al., 2021). To establish rudimentary yet functional engineering controls necessitates a change of mindset as one would change towards being pragmatic, rather than perfection. Nigeria's LEV system would be unable to satisfy the industrial ventilation standards of flow rate or capture efficiency. Nonetheless, it is meaningful harm reduction that is way better in comparison with unregulated exposure. The U.S. professionals who have to operate with limited funds and budgets can follow this philosophy: interim solutions that prove their effectiveness should be introduced, and more far-reaching controls should be sought.

Extended Producer Responsibility is the most resilient way to secure the supply chain. EPR laws require manufacturers to be in charge of recycling products after use, developing finances to ensure that the products designed are not so dangerous and provide formal recycling specifically through chain initiatives (Jardosh & Kathuria, 2025). The Rwanda pilot of the circular economy proves that this method has concomitant economic and health effects, as it generates revenue for the national budget and cuts exposures to the workers by 65 percent. Federal laws on EPR in the U.S. would profoundly change the trends in e-waste flows, decreasing the number of hazardous substances that are sold to informal industries in other countries (Weghmann, 2020). This deals with

transboundary liability exposure to the U.S. corporations under the Environmental, Social, and Governance standard of ensuring ethical labor practices within all the supply chains (Singh et al., 2020). In addition to compliance with regulations, EPR generates economic frameworks that rationalize profitability and worker safety, which occupational health is not an external issue of concern.

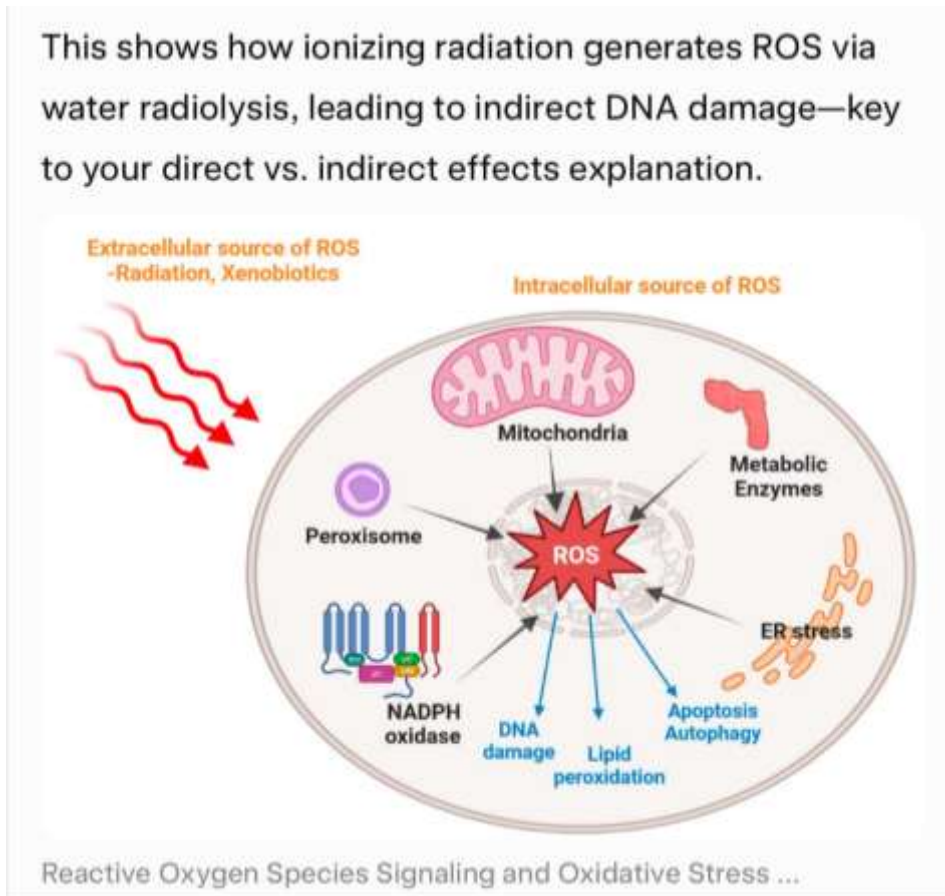


Figure 9. ROS Formation and Oxidative Stress (Radiation Interaction with Biological Tissues)

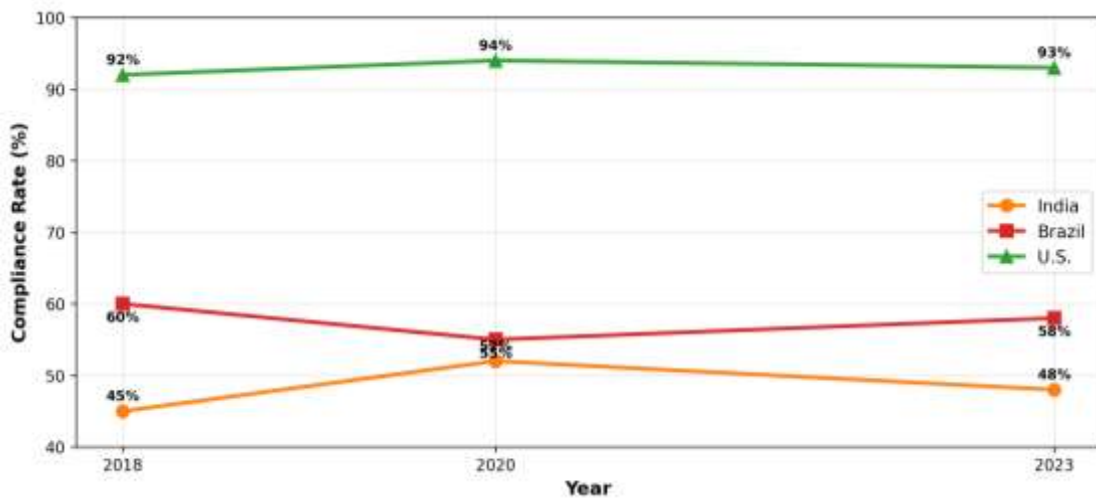


Figure 10. Regulatory Compliance Trends (2018-2023)

CONCLUSIONS AND RECOMMENDATIONS

The U.S. hazardous waste management framework is the international standard on occupational health protection (U.S. EPA, 2023). The standards of RCRA and OSHA are not a bureaucratic load, but the protocols of saving lives, which is reasonable because of the great toxicity of predominant waste streams (Grant et al., 2013). The medical study has three major suggestions to U.S. specialists. First, be very strict with domestic compliance because regulations react to actual healthcare dangers reported worldwide (Karagulian et al., 2019). Adherence cannot be taken as an administrative requirement but rather an involvement in a system, which has significantly minimized occupational illness. Second, audit supply chains across international borders to determine and ensure transboundary exposure risks posed by export e-waste and other dangerous substances are avoided (Perkins et al., 2014). The corporations of the United States have a collective liability towards the working conditions in the plants that process their end-of-life products, regardless of whether they are located within the jurisdiction of the United States or not. Third, deploy low-cost international innovations to resource-constrained home activities through the incorporation of modified engineering criteria, administrative monitoring frameworks, and reusable personal protective equipment practices (Kaza et al., 2018; Kumar et al., 2023). The certified professionals minimize occupation illness and the loss the economy would otherwise lose yearly (through waste) up to 10 to 15 billion dollars by connecting the U.S. regulatory know-how with evidence-based innovation, which safeguards the health of workers and the integrity of the global supply chain in its entirety (World Bank, 2022).

These recommendations can be implemented by are willing to engage in the process of continuous improvement at the professional level. The field data collection of the effectiveness of the control against limited resources in an industrial environment should be given significant emphasis by the industrial hygienists, as they add to the body of evidence concerning the feasible resources to solve the problem. Supply chain audits should be done by certified hazardous materials managers, not only according to minimum regulations but also according to the international occupational health conditions in recycling activities. Low-cost controls should not be viewed as quick fixes, but as interim measures that should be embraced by safety professionals as the only solution in the short term when capital limitations do not allow the full implementation of hierarchy. The multi-disciplinary strategy will provide the U.S. occupation health expertise to help in the lessening of the worldwide disease load and home domain supremacy.

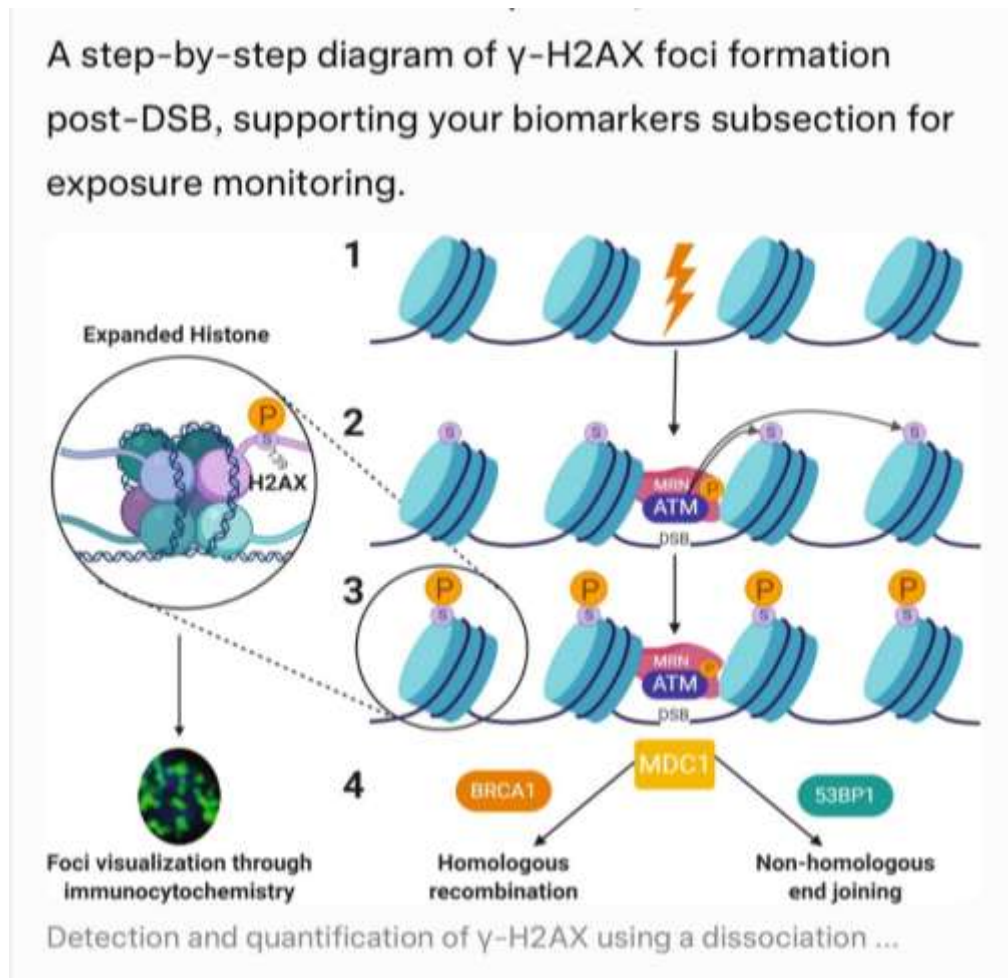


Figure 11: γ -H2AX as a Biomarker (Cellular and Molecular Responses)

ADVANCED RESEARCH

The limitation of this review is that the case study documentation and published literature were used as the basis of the study instead of field research, which was limited by resources. It targeted Ghana, Nigeria, Pakistan, India, and Rwanda so that the results could not be broadly generalized to other areas (Grant et al., 2013). There is a lack of quantitative data on the cost-effectiveness of modified controls, which limits its use to carry out an economic analysis of implementation at scale in the U.S. context (Karagulian et al., 2019). Future research ought to involve the direct field implementation studies of low-cost engineering controls in the U.S. small quantity generator plants, economic evaluation of adjusted and conventional control costs over several years of the deployment of the low-cost control combinations, and longitudinal health surveillance studies of the changes in biomarkers after the low-cost control combinations have been implemented. A study that investigates the hindrances to the adoption of modified control strategies in resource-strained organizations would inform diffusion (Dumka & Shukla, 2025). Lastly, comparative research on enforcement mechanisms that may lead to the formalization of the informal recycling industry would further the policy suggestions on Extended Producer Responsibility (Ferronato & Torretta, 2019).

Occupational health professionals are offered and challenged by the shift toward the models of a circular economy. The structure of waste streams will change as manufacturers design objects that can be reused and recycled at the end of their life, and not discarded. The occupational health contribution during product development stages is necessary to reduce occupational hazards in the design of products by adopting substitution and elimination strategies. Building organized recycling facilities in developing countries requires technical support in hazard assessment and control measures. The international cooperation in occupational health capacity building serves to ensure that formalization of the informal sector does not take place by seeing the protection of workers as a central issue, but as marginal. This has increased the role of occupational health professionals beyond the conventional working environment to influence the world supply chain architecture.

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