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Chemical Disasters: Human Health and Environmental Impacts, Regulatory Challenges and Management Strategies—A Review

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Abstract:

Chemical disasters are catastrophic accidents caused by the accidental release, leakage, explosion and fire involving hazardous chemicals from industrial units, storage units, transportation systems. These disasters cause severe threats to community health, ecosystems, infrastructure and socioeconomic stability. The Bhopal gas tragedy like historic incidents demonstrate the devastating acute and chronic consequences of toxic exposure. This review paper identifies the causes, health effects, environmental impacts, major global and current Indian case studies, regulatory frameworks, existing gaps in disaster management systems and policy recommendations to prevent future chemical disasters. It highlights the urgent need for stronger industrial safety mechanisms, real-time monitoring, modernized regulations,systems and community-based preparedness strategies to reduce chemical disaster risks.

Keywords: Chemical disasters, toxic exposure, industrial accidents, public health, Bhopal gas tragedy, disaster management, industrial safety regulations and hazardous chemicals.

1. Introduction:

Chemical disasters occur as a result of accidental and unintentional release, leakage, explosion, fire or exposure to harmful chemicals in solid, liquid or gaseous form[1]. Such incidents usually start off from industrial plants, laboratories[2], transportation systems, storage facilities or pesticide industries[3]. These disasters have severe effects on human health, animals, water resources, soil quality and atmosphere[4]. Swift industrialization, urbanization and excess use of hazardous chemicals have significantly increased the chances of industrial accidents worldwide. Bhopal gas tragedy like events have exposed the disastrous consequences of inadequate industrial safety systems and poor emergency preparedness. Chemical disasters cause immediate casualties in addition to long-term environmental pollution and intergenerational health effects.

To prevent and control disasters effectively there is a need of comprehensive risk assessment, advanced safety engineering, strict regulatory oversight and well-organized emergency response planning.

2. Methodology of Review:

For this review paper relevant literature has been searched using Google Scholar, Scopus, Web of Science, PubMed, WHO, UNEP and NDMA databases. Government reports, peer-reviewed journal articles and international safety guidelines have been reviewed and analyzed to examine causes, health impacts, environmental consequences, regulatory frameworks and management strategies linked with chemical disasters.

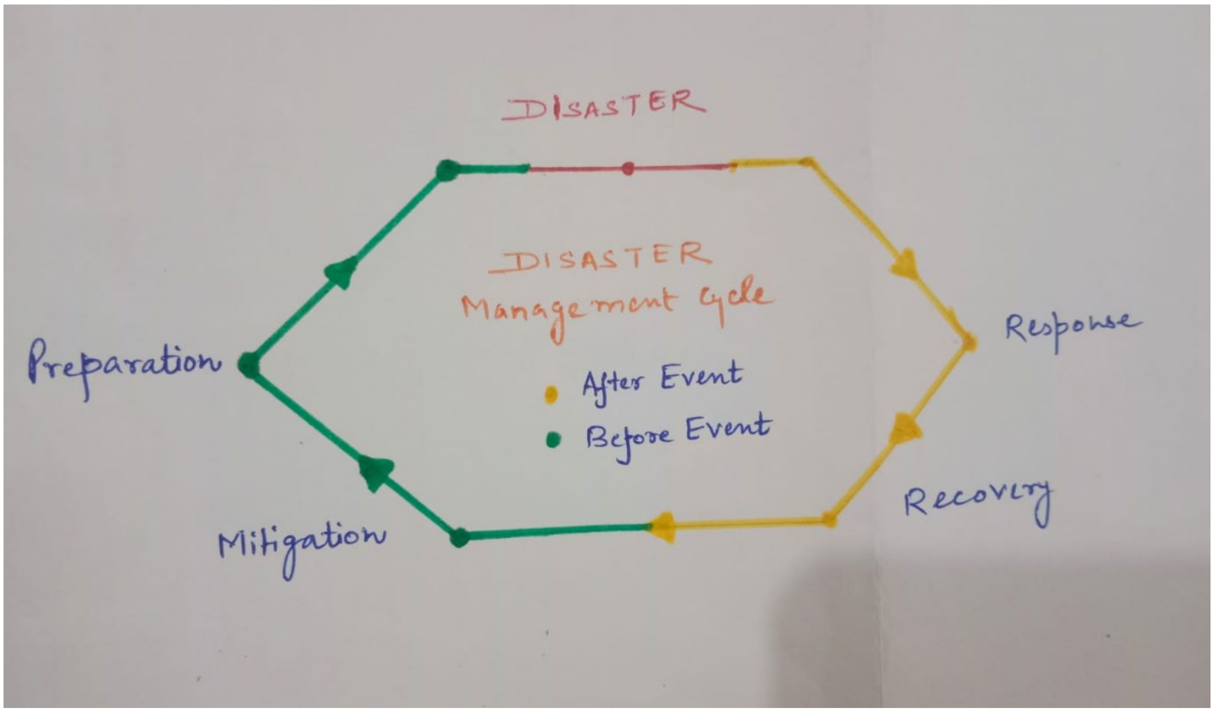

Figure 1. Chemical Disaster Management Cycle showing pre-disaster risk reduction (mitigation and preparedness), disaster occurrence, emergency response and post-disaster processes for sustainable recovery for minimizing disaster impacts.

3. Causes of Chemical Disasters-

Chemical disasters occur usually because of environmental, technical, organizational and human associated failures[5].

3.1 Industrial and Technical Failures:

Main industrial causes include:

- Machinery failure
- Expired industrial infrastructure
- Poor plant maintenance
- Substandard plant design
- Breakdown of cooling and pressure-control systems

Above factors appreciably increase the chances of chemical leakage, fires and explosions[6].

3.2 Human fault:

Human-related causes include:

- Insufficient employee training
- Disobedience of safety procedures
- Operational negligence
- Poor handling of hazardous chemicals
- Failure to follow emergency protocols

Above factors are the most common resulting in industrial accidents worldwide[7].

3.3 Natural Hazards:

Earthquakes, cyclones, floods and lightning like natural disasters may damage industrial establishments and start secondary chemical emergencies generally referred to as Natech (Natural Hazard Triggered Technological) disasters[8].

3.4 Transportation and Storage Accidents:

Chemical spills and explosions often occur during:

- Pipeline leakage
- Road transportation
- Railway transport
- Maritime transport
- Storage tank leakages

Above mentioned transportation linked accidents often result in environmental pollution and community exposure risks[9] in large-scale.

4. Impact of Chemical Disasters on community Health-

Chemical disasters have severe effects on community health through inhalation, ingestion and dermal exposure pathways. Health effects may be acute or long-term chronic.

4.1 Acute Health Effects:

Severe respiratory and systemic complications occur as a result of direct exposure to lethal chemicals depending on the nature, amount and extent of exposure. Acute exposure generally produces respiratory complications including pulmonary edema, pneumonitis and respiratory failure etc. Such acute lethal manifestations were extensively reported during the Bhopal gas tragedy due to methyl isocyanate chemical exposure.

4.2 Chronic Health Effects:

Persistent respiratory, immunological, neurological and carcinogenic effects[10] occur due to chronic exposure to dangerous industrial chemicals. Long-term exposure may result in :

- Cataracts and chronic eye diseases
- Chronic obstructive pulmonary disease
- Pulmonary fibrosis
- Neurological impairment
- Cognitive dysfunction

Studies carried out after major industrial accidents have shown that chronic illnesses and disability may last for many years among exposed populations.

4.3 Reproductive and Genetic Effects:

Reproductive and genetic health is affected drastically due to chemical disasters as many harmful chemicals possess mutagenic, teratogenic and endocrine-disrupting properties[11&12]. Many reported reproductive and genetic impacts may result in :

- Infertility
- Miscarriages
- Stillbirths
- Congenital abnormalities
- Intergenerational genetic disorders

4.4 Psychological Impacts:

Psychological trauma is the most ignored consequence of chemical disasters and frequently persists much after physical recovery. Survivors usually face:

- Nervousness
- Depression
- Post-traumatic stress disorder
- Social trauma
- Economic insecurity

5. Environmental Impacts of Chemical Disasters-

Long-lasting effects on environmental components occur due to Chemical disasters. The discharge of harmful chemical substances into the environment can disturb ecological balance, degrade natural resources and cause considerable risks to community health and biodiversity (WHO, 2018; UNEP, 2019).

5.1 Impacts on Air Quality:

Discharge of toxic gases, aerosols and particulate matter into the atmosphere occur due to chemical disasters. Many hazardous chemicals such as CH_3NCO, NH_3, Cl_2, SO_2 and volatile organic compounds etc. may spread over wide geographical areas causing acute and chronic health effects. Airborne harmful substances can result in eye irritation, respiratory illnesses, pulmonary edema and increased death rate. Also these pollutants can lead to the formation of acid rain, photochemical smog etc. and destroy vegetation through impaired photosynthesis and decreased plant productivity[13].

5.2 Impacts on Water Resources:

The discharge of chemicals into water resources like rivers, lakes, groundwater and coastal ecosystems can adversely affect water quality[14]. Harmful substances can change physicochemical properties of water, decrease dissolved oxygen concentrations and increase toxicity levels resulting in fish killing and damage of aquatic biodiversity. Some persistent harmful chemicals may bioaccumulate in aquatic organisms and biomagnify through food webs causing risks to wildlife and human life depending on the contaminated water resources. Groundwater contamination for a longer period has been reported in many chemical disaster places including the Bhopal region and it has affected drinking water quality and community health for many years[15].

5.3 Impacts on Soil Quality:

Chemical disasters result in chemical discharge and atmospheric deposition of unsafe substances. These may result in soil contamination by heavy metals, hydrocarbons and other toxic compounds changing soil physicochemical properties, decreasing microbial diversity, damaging nutrient cycling and reducing agricultural productivity. Persistent pollutants can exist in soils for longer periods escalating the risk of uptake by crops and successive entry into the food chain and leading to considerable ecological, economic and food security consequences[16].

5.4 Integrated Ecosystem Effects:

The impacts of chemical disasters on air, water and soil are interrelated . Atmospheric deposition can transport harmful chemicals from air to terrestrial and aquatic ecosystems while contaminated soils may act as sources of groundwater contamination through leakage. These exchanges may cause biodiversity loss, habitat degradation, disturbance of ecosystem services and long-standing ecological instability. So efficient environmental monitoring, hazard assessment and remediation preparation are vital components of chemical disaster management[17&18].

6. Major Chemical Disaster Case Studies-

6.1 Comparative Overview of Major Chemical Disasters:

Disaster	Year	Location	Cause	Major Impacts	Policy Outcomes

Bhopal Gas Tragedy	1984	[19]Bhopal	MIC gas leakage from pesticide plant	>3000 immediate deaths, Pulmonary damage, blindness, groundwater contamination, congenital abnormalities	Environment Protection Act[5], 1986; stronger industrial safety regulations
Texas City Disaster	1947	[20]Texas City	Explosion of ammonium nitrate cargo ship	581 deaths, fires, infrastructure destruction	Improved maritime safety standards
Seveso Disaster	1976	[21]Seveso	Uncontrolled chemical reaction releasing TCDD	Chloracne, soil contamination, cancer risks	European Union Seveso Directives
Tianjin Explosions	2015	[22]Tianjin	Improper hazardous chemical storage	173 deaths,firefighter fatalities, cyanide contamination	National industrial safety crackdown

7. Recent Industrial Chemical Accidents in India (2025–2026)-

7.1 Telangana Reactor Explosion[23]:

In July 2025, a huge reactor explosion and fire occurred at a pharmaceutical manufacturing unit operated by Sigachi Industries in Pashamylaram near Hyderabad. Many sections of the production facility were collapsed in the explosion and caused several fatalities and injuries among employees. Preliminary investigations suggested too much reactor pressure buildup, overheating and collapse of industrial safety systems. In this event failure of pressure-control mechanisms, poor compliance monitoring, inadequate emergency preparedness were indicated.

7.2 Gujarat Industrial Explosion[24]:

In April 2026, a major fire broke out in Metropolitan Eximchem Pvt Ltd in the Jhagadia industrial estate of Bharuch as a result of a powerful explosion. The explosion created extensive smoke emissions resulting in multiple employee injuries. Apparent Causes were improper hazardous chemical storage, failure of containment systems and insufficient fire suppression mechanisms.

7.3 Karnataka Chemical Storage Explosion[25]:

In February 2026, in Mandya district of Karnataka, an accidental explosion occurred during dismantling operations at an industrial facility. The blast occurred in a chemical storage tank and caused worker fatalities and severe injuries. Preliminary reports suggested procedural failures during dismantling, poor hazardous material handling, lack of technical supervision and insufficient worker safety training.

7.5 Key Lessons from Recent Indian Incidents:

These industrial disasters jointly display persistent weaknesses in industrial safety governance in India, including insufficient preventive maintenance, weak safety auditing systems, poor emergency preparedness and inadequate worker protection mechanisms (NDMA, 2020; OECD, 2015; ILO, 2014). These incidents highlight the importance for modernized process safety management systems, real-time monitoring technologies, automated hazard detection systems and stricter regulatory enforcement in rapidly expanding chemical and pharmaceutical industries. Studies on industrial accident prevention suggest that failures in safety culture, maintenance systems and worker training remain among the major contributors to frequent industrial disasters in developing economies.

8. Critical Analysis-

8.1 Critical Analysis of the Bhopal Gas Tragedy:

The Bhopal gas incident exposed the major weaknesses in industrial risk management, particularly the absence of adequate maintenance systems, emergency planning and public awareness mechanisms. Although safety systems work on paper, many were either non-functional or intentionally shut down to reduce operational costs. This disaster demonstrated how economic priorities and weak regulatory enforcement can considerably increase industrial vulnerability in India like developing countries.

8.2 Critical Analysis of Indian Regulatory Framework:

In India, there is comprehensive legislative framework for chemical disaster management but enforcement remains inconsistent. Regulatory mechanisms normally emphasize documentation-based compliance rather than physical safety verification. Many industrial units successfully pass inspections despite poor maintenance standards, signifying that institutional weaknesses and administrative fragmentation reduce the practical effectiveness of existing laws.

8.3 Critical Analysis of Safety Audits:

Several studies suggest that industrial safety audits in developing economies frequently function as routine formalities rather than precise technical evaluations. Industries often conduct pre-announced inspections, which allow short-term corrections that cover deeper structural deficiencies. As a result of this poor audit culture, chances of recurring industrial accidents become more.

8.4 Critical Analysis of Emergency Response:

Several chemical disasters expose that emergency response systems are reactive rather than preventive, mostly in densely populated industrial regions of developing countries (NDMA, 2020; WHO, 2018). On average there is lack of toxicological expertise, chemical decontamination facilities, antidote stockpiles and specialized emergency preparedness protocols (ILO, 2014) in the hospitals located near these industrial clusters.

Studies investigating major industrial accidents reveal that the initial few hours after toxic exposure are frequently characterized by late diagnosis, poor communication, weak evacuation coordination and inadequate availability of protective equipment for emergency responders. Investigations following recent industrial incidents in India have similarly exposed many gaps in onsite emergency systems, evacuation planning and coordination between industries, local administration and healthcare services.

The Bhopal gas tragedy is one of the most noteworthy examples of emergency response failure where insufficient public warning systems, inadequate medical preparedness and lack of toxicological information extensively increased mortality and long-term health impacts among exposed populations (NDMA, 2020).

9. Regulatory Framework in India-

9.1 Major Legislative Frameworks:

Disaster Management Act, 2005

Provides the national framework for disaster management through the National Disaster Management Authority (NDMA).

MSIHC Rules, 1989

Directs hazard identification, safety audits and emergency planning.

Chemical Accidents Rules, 1996

Establishes crisis groups and off-site emergency mechanisms.

Public Liability Insurance Act, 1991

Provides instantaneous compensation to victims of chemical accidents.

Factories Act, 1948

Enforces industrial workplace safety measures.

10. Gaps in the Current System-

10.1 Workforce Vulnerabilities:

- Inadequate safety training for contractual workers
- weak emergency preparedness
- Less worker participation in drills

10.2 Emergency Response limitations:

Chemical disaster management systems in developing countries normally have considerable infrastructural and operational limitations during emergencies (NDMA, 2020; WHO, 2018). Major limitations include:

- Encroachment near industrial sites
- Weak off-site evacuation systems
- Less toxicological facilities in hospitals
- Poor hazardous transport tracking

Studies investigating industrial emergency situations point out that delayed evacuation, inadequate coordination between agencies, poor protective equipment and weak medical preparedness extensively increase disaster severity and death rates (OECD, 2015; ILO, 2014).

11. Policy Recommendations-

11.1 Regulatory Reforms:

- Swift implementation of CMSR ("India REACH")
- Formation of a unified national chemical safety authority
- Review of hazardous chemical thresholds

11.2 Strengthening Enforcement:

- Real-time monitoring systems
- Autonomous third-party safety audits

11.3 Employee and Community Safety:

- Compulsory safety training for all employees
- Enforcement of industrial buffer zones
- Society-based evacuation drills

11.4 Medical Preparedness:

- Advanced toxicology centers
- Emergency antidote reserves
- Chemical decontamination centers

12. Artificial Intelligence (AI) and Emerging Technologies in Chemical Disaster Management-

12.1 AI for Risk Prediction and Prevention[26&27]: AI has emerged as a powerful tool for predicting and preventing chemical disasters prior to their occurrence. Traditional industrial safety systems frequently rely on periodic inspections and manual monitoring which may fail to recognize upcoming risks in real time. AI algorithms may study sufficient operational data collected from industrial equipment, sensors, maintenance records and past accident databases to identify patterns associated with equipment failure, chemical leaks, explosions and fire incidents. Use of AI can help predictive maintenance systems to forecast when machinery is likely to fail, thereby advising industries to conduct repairs proactively and minimize accident risks. Such predictive capabilities may considerably reduce the occurrence of industrial accidents and ensure overall plant safety.

12.2 AI-Based Monitoring and Early Warning Systems[28&29]: Real-time monitoring is vital part of chemical disaster prevention and response. AI-driven monitoring systems incorporate data from Internet of Things (IoT) devices, environmental sensors, surveillance cameras, drones and satellite observations to regularly assess industrial circumstances. These systems can quickly sense toxic chemical emissions, poisonous gas leaks and fire outbreaks. After detecting dangerous conditions, AI algorithms can process sensor data in real time and automatically trigger warning alerts. Advanced systems can approximate the quantity of emitted chemicals, forecast the direction of toxic cloud movement and recognize public at risk. Such technologies considerably help in better preparedness and minimize casualties during chemical disasters.

12.3 AI in Emergency Response and Medical Management[30]: In chemical disasters, quick decision-making is important to reduce loss of life and environmental damage. AI-based decision support systems can assist emergency responders by analyzing real-time information and recommending suitable response strategies. These systems can optimize evacuation routes, allocate emergency resources efficiently and recognize safe access points for rescue teams. In healthcare settings, AI may help in diagnosis and treatment of chemical contact sufferers.. Also, AI can help in communication and coordination among hospitals, emergency services and disaster management agencies resulting in overall better response.

12.4 Digital Twins and Disaster Simulation[31-33]: Digital twin technology includes AI, real-time sensor data and computer simulations to generate virtual replicas of chemical plants, industrial facilities, storage systems and transportation networks. These digital models constantly reflect the current operating circumstances of physical systems and may be used to simulate accident scenarios prior to their occurrence. Digital twins permit industries and disaster management authorities to assess the potential consequences of chemical emissions, explosions, fires and equipment failures under different situations. Emergency response strategies may be tested and refined using simulated disaster scenarios without exposing people or infrastructure to actual risks. By identifying vulnerabilities and testing mitigation strategies in advance, digital twins can contribute appreciably to disaster prevention and preparedness.

12.5 Challenges and Future Directions[34-36]: Despite their considerable potential, emerging technologies particularly AI, in chemical disaster management faces numerous challenges. In developing countries, many industries lack the necessary digital infrastructure, sensor networks and data management systems needed for effective AI deployment. The accuracy of AI models heavily relies on the quality and availability of data . As a result partial or unreliable datasets may lead to incorrect predictions. Additional concerns include system reliability, cyber security threats, high implementation costs and the limited availability of skilled staff capable of managing advanced AI systems. Smart industrial safety systems having autonomous risk detection, real-time risk assessment and programmed emergency response can significantly minimize the number and severity of chemical disasters.

13. Conclusion:

Chemical disasters are the major industrial and environmental challenges worldwide, causing extensive human suffering, ecological degradation and economic losses. This review highlights that chemical accidents occur due to human errors, technical failures, insufficient safety culture, transportation mishaps and natural hazard-triggered technological events. Historical disasters such as Bhopal gas tragedy, Texas City explosion and Tianjin explosions etc. demonstrate the devastating short-term and long-term consequences of toxic chemical emissions on human health, ecosystems and socioeconomic systems.

The review further reveals that chemical disasters can result in acute health effects, chronic respiratory and neurological disorders, reproductive abnormalities, genetic impacts and significant psychological trauma among affected populations. Environmental consequences include persistent contamination of air, water and soil resources, disturbance of ecological processes, biodiversity loss and long-term risks to food security and public health. Recent industrial incidents in Telangana, Gujarat and Karnataka indicate that industrial growth continues to be accompanied by substantial safety challenges, emphasizing the need for stronger preventive mechanisms and regulatory compliance.

Although India possesses an extensive legislative framework for chemical disaster management, significant gaps remain in enforcement, safety auditing, workers training, emergency preparedness, risk communication and medical toxicology infrastructure. There is requirement of a shift from reactive response approaches to proactive prevention strategies based on risk assessment, process safety management, real-time monitoring and public participation for the effective disaster risk reduction. Emerging technologies particularly AI offer significant opportunities for enhancing industrial safety and disaster preparedness.

In conclusion, protecting human health and the environment must be the central objective of industrial development and chemical safety management in the twenty-first century.

CONFLICT OF INTEREST: The author declares that I have no affiliation with or involvement in any organization or entity with any financial or nonfinancial interest in the subject matter or materials discussed in this manuscript.

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