

# Occupational Health Hazards and Safety Mitigations in India's Emerging Semiconductor Manufacturing Sector

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**Abstract:** Semiconductor manufacturing is expanding in India through the establishment of new fabrication, assembly, testing, marking, and packaging facilities. Although this growth supports strategic electronics manufacturing, it also introduces complex occupational health and safety risks. Semiconductor facilities use hazardous chemicals, toxic and pyrophoric gases, high-energy equipment, cleanroom systems, ergonomic tasks, and tightly controlled production environments. This manuscript reviews the major occupational hazards and safety best practices relevant to Indian semiconductor manufacturing. Using a narrative literature and policy review, it draws on semiconductor occupational health studies, chemical exposure research, international safety guidance, and India's regulatory framework to identify the gaps. The review found that the most significant hazards include exposure to acids, solvents, dopant gases, photoresists, plasma by-products, noise, radiation, ergonomic strain, heat stress, shift work, and psychosocial stress. In India, best practices should integrate the Occupational Safety, Health and Working Conditions Code, hazardous chemical rules, factory licensing, process safety management, real-time gas detection, medical surveillance, emergency preparedness, and worker participation. The study concludes that India's semiconductor growth must be matched by strong environmental, health and safety (EHS) systems, transparent exposure monitoring, and sector-specific occupational health research.

**Keywords:** semiconductor manufacturing, occupational health, India, cleanroom safety, chemical hazards, EHS, process safety

## 1. INTRODUCTION

Semiconductors power computers, mobile devices, telecommunications, automobiles, defense systems, and artificial intelligence, making them the foundation of modern electronics. There are four main types of semiconductors: memory, microprocessors, standard chips or commodity integrated circuits, and system-on-chip (SOC) that enable miniaturization and the lighter, faster, and smarter capabilities of the devices. In India, past investments in the semiconductor ecosystem have been integrated into a complete value chain of design, expansion, fabrication, assembly, and testing facilities (silicon fabs, silicon carbide fabs, advanced and memory packaging facilities) to meet the growing chip needs of key sectors such as consumer appliances, industrial electronics, automobiles, telecommunications, aerospace, and power electronics. Of these approved proposals, some use indigenous technologies to assemble, test, and package semiconductor chips, which represent a deeper technological capability and reduced reliance on external systems and a higher place in the global semiconductor value chain for India.

Semiconductor manufacturing is one of the most technologically advanced and chemically intensive industrial sectors in the world, with wafer fabrication, chip packaging, assembly, and testing processes involving photolithography, etching, ion implantation, diffusion, chemical-mechanical polishing, cleaning, deposition, and metrology, requiring highly controlled cleanrooms and the extensive use of acids, bases, solvents, specialty gases, metals, polymers, plasma systems, and high-energy equipment. India is trying to create a domestic semiconductor ecosystem by building fabrication units, assembly test facilities, compound semiconductor units, design-linked incentives, and supply chains localization. This brings jobs and technological capacity, but it also brings occupational health hazards that may not be familiar to traditional manufacturing regulators, contractors, and local emergency responders.

Semiconductor facilities are not standard electronics factories; they present a combination of chemical plant risks, precision manufacturing risks, cleanroom risks, and high-throughput production pressure. A number of studies in Korea have investigated chemical use, environmental changes, biomarkers of exposure, and compensation claims for cancer and rare diseases, which are not India-specific but have applicability to India as it enters the same technology domains and avoids repeating preventable occupational health hazards.

Figure 1. illustrates the key trends in semiconductor safety.

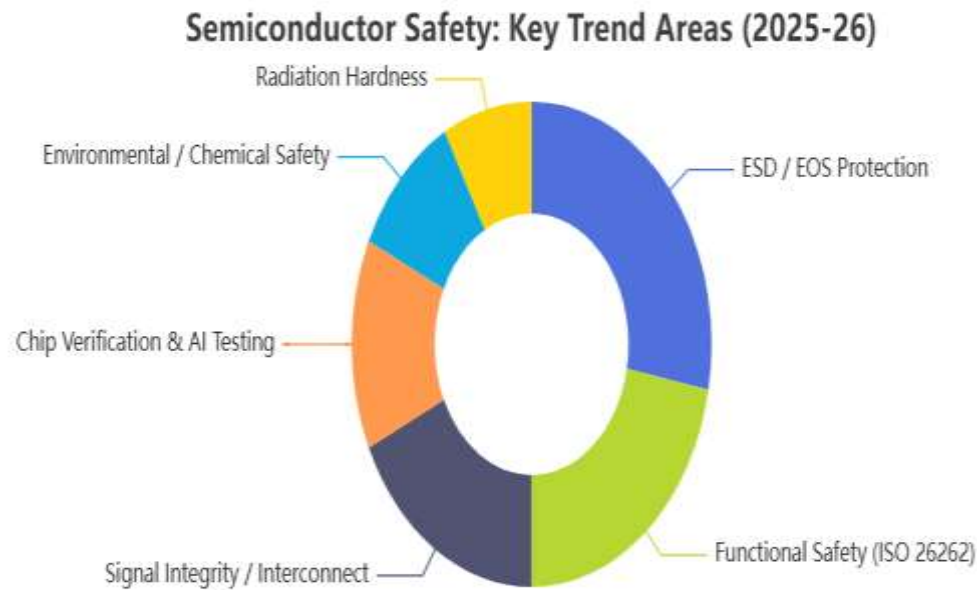


Figure 1. Semiconductor Safety: Key Trend Areas

Securing the physical manufacturing facility (option 1) and guaranteeing the digital dependability of the chips (option 2) are two strategies that are necessary for semiconductor safety.

#### Option 1: Fab and Workplace Safety

Fabrication facilities (fabs) handle highly hazardous materials and require extreme environmental and occupational safety protocols.

- **Advanced Gas Detection:** Fabs rely on real-time **Fourier Transform Infrared (FTIR) spectroscopy** to detect ultra-low parts-per-billion (ppb) leaks of lethal gases such as silane, arsine, and hydrogen fluoride.
- **Chemical Exposure Control:** Automated chemical delivery systems (CDS) isolate workers from toxic acids, solvents, and specialty dopants used in wafer etching and deposition.
- **Sub-Fab Automation:** Heavy maintenance and gas cylinder changeouts in the sub-fab are increasingly performed by autonomous mobile robots (AMRs) to eliminate human exposure to toxic zones.
- **Per- and Polyfluoroalkyl Substances (PFAS) Mitigation:** Fabs face massive regulatory pressure to phase out or strictly capture PFAS chemicals, which are heavily used in photolithography and surfactant processes.
- **Ergonomic Cleanroom Automation:** Automated Material Handling Systems (AMHS) use overhead transport tracks to move heavy wafer pods, eliminating manual lifting injuries in cleanrooms.

#### Option 2: Hardware Functional Safety

Chip architectures must be designed to detect, isolate, and recover from failures in mission-critical applications such as automotive, aerospace, and medical devices.

- **ISO 26262 & Automotive Safety:** Modern chips require Automotive Safety Integrity Level (ASIL) ratings—specifically **ASIL-D for autonomous driving**—ensuring that the hardware handles random physical failures without crashing the vehicle.
- **Dual-Core Lockstep (DCLS):** Safety-critical processors run identical operations on two parallel cores simultaneously, comparing outputs every clock cycle to instantly detect transient faults caused by cosmic rays or electrical noise.
- **Built-In Self-Test (BIST):** Chips use dedicated logic and memory BIST hardware to run self-diagnostic routines during startup and runtime, predicting failures before they occur.
- **Hardware Security Modules (HSM):** Isolated on-chip security enclaves manage cryptographic keys and secure boot processes, preventing malicious codes from overriding physical safety controls.

- **Hardware-Root-of-Trust (RoT):** Silicon-level anchors prevent hardware-based supply chain attacks, ensuring that the chip cannot be cloned, tampered with, or injected with malicious trojans during manufacturing.

## 2. PROBLEM STATEMENT

India's semiconductor manufacturing sector is emerging faster than the country's sector-specific occupational health evidence. General factory safety laws and hazardous chemical rules exist, but semiconductor facilities require specialized controls for toxic gases, hydrofluoric acid, pyrophoric gases, cleanroom ergonomics, nanomaterials, radiation sources, high-voltage equipment, chemical waste, and emergency responses. Therefore, the problem is twofold.

1. Occupational hazard complexity: Semiconductor manufacturing exposes workers to low-volume but high-consequence hazards, including toxic gases, corrosive chemicals, solvents, process by-products, radiation, ergonomic risks, and psychosocial stress.
2. Indian implementation gap: India's regulatory framework provides a broad legal basis for worker safety, including the Occupational Safety, Health, and Working Conditions Code, 2020, but semiconductor-specific EHS implementation, exposure databases, medical surveillance protocols, and emergency preparedness systems are still evolving.

If safety systems are not designed early, India may face preventable chemical incidents, chronic occupational diseases, contractor injuries, environmental releases, and reputational risks in a sector that depends on reliability, precision, and global compliance.

## 3. OBJECTIVES

The objectives of this study are as follows:

1. Identify major occupational health hazards in semiconductor manufacturing facilities.
2. Examine the best safety practices applicable to fabrication, assembly, testing, and cleanroom operations.
3. Interpret these hazards and controls in the context of Indian regulations and industry practices.
4. A practical EHS framework for Indian semiconductor facilities is proposed.
5. Identifying future research priorities for occupational health surveillance in India's semiconductor sector.

## 4. LITERATURE REVIEW

Yoon, C.'s (2012) study stated that semiconductor industry is a novel industry that was founded in the late twentieth century, and the lack of scientific evidence on occupational health and environmental issues also exists, in part, because of its relative youth. The corporate veil of secrecy shields many unknown constituents in chemicals, and the effects of these constituents have yet to be investigated. The semiconductor industry has long been of concern to the public, due to the large number of chemicals employed, the frequency of process changes, the lack of available public exposure data, and the difficulty in connecting chronic disease outcomes to specific exposures [1].

Yoon et al. (2020) stated that the central issue is chemical exposure, and research on Korean semiconductor workplaces found that understanding the status of chemical use and safety data sheets at major semiconductor facilities is essential [2]. This is significant for India because fabs and Outsourced Semiconductor Assembly and Test (OSAT) facilities may utilize imported process chemicals, proprietary blends, and supplier-controlled formulations, which can make risk assessment incomplete without a robust chemical inventory, safety data sheet (SDS) verification, substitution review, and exposure monitoring system.

Kim, K. et al. (2022) presented that studies of Korean semiconductor workers between 1984 and 2012 reported changes in work environments, health status, and risk factors, demonstrating that semiconductor hazards evolve as processes, materials, and automation levels change [3]

Kim, K., and Sung, H. K. (2022) stated that his biological monitoring studies evaluated the possible exposure to carcinogens by semiconductor workers including biomarkers for benzene and other substances, which indicated that air monitoring may not be sufficient for mixed exposure, skin contact, or intermittent maintenance exposure [4]; hence, medical surveillance and biological exposure monitoring is justified in cases of risk assessment and should be considered in Indian semiconductor facilities.

Long-term disease tracking, job-exposure matrices, and transparent worker health records were emphasized by Park (2019) and Kim et al. (2013) based on occupational compensation records from Korean semiconductor workers with cancer and rare diseases [5] [6]. India needs to establish surveillance systems prior to disease clusters, integrating baseline health examinations, exposure histories, and longitudinal monitoring of semiconductor EHS management.

Safety climate is also considered a critical component to general occupational safety research by Stasiła-Sieradzka M (2020) [7], and safety programs are not dependent on equipment and procedures alone but also depend on worker participation, training, reporting culture, management commitment, and job-specific safety design. Due to this reliance on mixed workforces with permanent employees, contract workers, equipment vendors, and temporary workers, these safety programs must be built before disease

clusters occur in semiconductor facilities in India.

At a high level, India has an Occupational Safety, Health, and Working Conditions Code, 2020 to cover occupational safety and health. Hazardous chemicals and processes related to semiconductor manufacturing may also be covered by more specific factory rules, chemical storage, emergency planning, and environmental permits, although EHS guidelines for India are still evolving with the India Semiconductor Mission and new fab investments, which are best supplemented by international semiconductor standards and good practices such as SEMI S2, ISO45001, ISO14001, process safety management, and emergency response planning. Given that India is rapidly building out its domestic semiconductor fabrication ecosystem, we still have few direct epidemiological data on local fabs in the literature, and so the best safety practices and mitigation measures for cleanroom chemical/ergonomics would be drawn from global experience.

## 5.METHODOLOGY

This manuscript uses a narrative review methodology with three components.

1. Academic literature review: Semiconductor occupational health papers were reviewed to identify recurring hazards, exposure concerns, safety climate issues, and disease surveillance needs. The retrieved sources included studies on chemical use, biological exposure assessment, changes in work environment, and compensation claims.
2. Policy and regulatory scan: Indian occupational safety context was assessed using information retrieved from the Occupational Safety, Health, and Working Conditions Code, 2020 and semiconductor-sector EHS development.
3. Hazard-control mapping: Identified hazards were organized using the hierarchy of controls: elimination, substitution, engineering controls, administrative controls, PPE, emergency preparedness, and medical surveillance.

The review was qualitative rather than statistical. Because India-specific semiconductor occupational health studies are limited, international semiconductor literature was interpreted cautiously and applied to India as transferable industrial evidence and not as direct Indian epidemiological evidence.

## 6.RESULTS AND DISCUSSION

### 6.1 Major Occupational Health Hazards

Semiconductor production is critical to the global economy and depends on a group of chemicals called per- and polyfluoroalkyl substances (PFAS). Various types of PFAS are essential in semiconductor manufacturing because of their low surface tension, high heat and chemical resistance, high thermal stability, radiation stability, favorable electrical characteristics, compatibility with other chemicals, purity, and other properties that enable them to fulfil the unique demands of semiconductor manufacturing.

Fluoropolymers, fluorochemicals, and fluorinated gases are used by the industry to meet many needs within the manufacturing process and can be found in the following:

- Components used in factory water, liquid, gas, and exhaust distribution systems
- Components used in wafer-processing tools and factory control systems
- Specialized cleanroom design features
- Personal protective equipment
- Lubricants used in high-technology robotics and vacuum
- Heat transfer fluids and refrigerants for high-precision temperature-control units and process chillers
- Process chemicals in photolithography, dry etching, cleaning, and deposition to reduce the potential for defects and enable high-resolution microstructures and deliver required yield; and
- Semiconductor devices.

In summary, the semiconductor manufacturing process is enormously dependent on fluorine chemistry in a variety of use cases, the majority of which currently have no viable alternatives. The PFAS group includes thousands of substances in many subgroups: polymers and non-polymers, solids, liquids, and gases, persistent and non-persistent, highly reactive and inert, mobile and insoluble, and toxic and non-toxic. Frequently, efforts to address important health and environmental topics use the broad term PFAS when they are most interested in a distinct subgroup of PFAS, such as perfluoroalkyl acids, like perfluorooctanoic acid (PFOA), which is suspected to cause adverse human and ecological health effects.

### 6.1.1 Chemical hazards

Semiconductor facilities use hazardous chemicals such as hydrofluoric acid, sulfuric acid, hydrochloric acid, nitric acid, ammonium hydroxide, hydrogen peroxide, organic solvents, developers, photoresists, strippers, dopants, and cleaning agents. Hydrofluoric acid is particularly dangerous because it can penetrate tissues and cause systemic toxicity. The search for evidence on semiconductor chemical hazards identified substances such as hydrofluoric acid, arsine, phosphine, and silane as major safety concerns. Key health effects may include chemical burns, respiratory irritation, dermatitis, eye injury, systemic toxicity, neurotoxicity, reproductive concerns, and potential carcinogenic risks, depending on the substance and exposure route. Maintenance, chemical change-out, spill cleanup, wet bench work, waste handling, and tool servicing may present a higher exposure risk than normal automated production.

Best practices:

- Maintain a live chemical inventory with SDS verification and update it regularly.
- Closed chemical delivery systems should be used.
- Substitute less hazardous chemicals, where technically possible.
- Install local exhaust ventilation, wet scrubbers, and automatic shut-off systems.
- Require HF-specific emergency response, including calcium gluconate availability and trained first aid.
- Conduct routine air, surface, and biological monitoring where risk assessment indicates it.

### 6.1.2 Toxic, flammable, and pyrophoric gas hazards

Specialty gases used in semiconductor processes include silane, arsine, phosphine, diborane, ammonia, chlorine, hydrogen chloride, nitrogen trifluoride, fluorine-containing gases, hydrogen, and other dopant or etch gases. These gases may be toxic, corrosive, flammable, asphyxiating, or pyrophoric in nature.

Best practices:

- Gas cabinets with automatic sprinklers or fire suppression should be used where applicable.
- Continuous gas detection with alarm interlocks should be installed.
- Excess-flow valves, automatic shutoff valves, purge systems, and ventilated enclosures must be used.
- Segregate incompatible gas.
- Leak checks and preventive maintenance should be performed.
- Emergency responders should be trained on gas-specific hazards before plant commissioning.

### 6.1.3 Cleanroom-related ergonomic and physiological hazards

Cleanrooms reduce contamination but may also increase worker strain. Employees must wear full-body garments, gloves, masks, hoods, goggles, and shoe covers for long periods. Tasks often involve microscope inspection, repetitive hand movements, awkward postures, static standing, and precision in handling. The potential health outcomes include musculoskeletal disorders, eye strain, fatigue, heat stress, restricted movement, skin irritation, and dehydration.

Best practices:

- Use ergonomic workstations, adjustable seating, anti-fatigue mats, and lift-assistive devices.
- Rotating tasks to reduce repetitive strain.
- Design gowning protocols that reduce the heat burden.
- Hydration and rest breaks should be provided.
- An ergonomic review should be included during tool layout and process design.

### 6.1.4 Physical hazards

Semiconductor facilities contain high-voltage systems, radiofrequency generators, lasers, ionizing or non-ionizing radiation sources, vacuum systems, robotics, moving parts, pressure systems, cryogenics, hot surfaces, and noise. Maintenance technicians may face a higher risk during tool opening, troubleshooting, and lockout activities.

Best practices:

- Implement lockout/tagout systems to prevent accidental activation.

- Interlocked tool enclosures must be used.
- Radiation surveys should be performed where relevant.
- Maintain machine guarding and preventive maintenance schedule.
- Require permit-to-work systems for high-risk maintenance.

#### 6.1.5 Psychosocial and organizational hazards

Semiconductor production is often continuous, high-value, and time-sensitive in nature. Workers may experience shift work, night work, high production pressure, alarm fatigue, isolation in cleanroom environments, and stress due to strict quality control. Safety climate research suggests that occupational safety depends on job-specific safety culture and worker perception, not merely on written procedures.

Best practices:

- Fatigue risk management should be used for shift schedules.
- Encourage near-miss reporting without assigning blame.
- Include contract workers in the same safety culture as permanent staff members.
- Workload and overtime should be monitored.
- It is important to provide mental health and counseling support.

#### 6.1.6 Waste and environmental health hazards

Semiconductor plants generate chemical waste, spent solvents, acid waste, metal-bearing waste, contaminated PPE, filters, scrubber residues, and wastewater treatment sludge. Poor waste handling exposes workers and nearby communities.

Best practices:

- Waste should be segregated at the source.
- Use compatible containers and secondary containment systems.
- Monitor effluent and air emissions.
- Waste handlers and transporters should be trained.
- Integrate occupational safety and environmental compliance.

### 6.2 Indian Regulatory and Institutional Context

Regulatory standards for semiconductor manufacturing plants (**Fab Safety**) focus on environmental compliance, chemical tracking, and worker protection, while standards for the chip architectures themselves (**Hardware Functional Safety**) govern system reliability and fault isolation.

The primary regulatory and industry standards driving both domains include:

#### 6.2.1 Fab and Workplace Safety Standards

To maintain compliance and workplace safety, facilities follow specific industry standards and guidelines. While global government agencies enforce localized laws—such as OSHA in the US and state pollution control boards globally—the global semiconductor manufacturing ecosystem relies heavily on highly targeted international frameworks:

- **SEMI S2 & SEMI S8 (Industry Benchmarks):** Published by semiconductor equipment and materials international (SEMI), SEMI S2 dictates environmental, health, and safety evaluations for all manufacturing equipment. SEMI S8 lays out ergonomic requirements to minimize repetitive strain injuries for cleanroom operators.
- **TSCA & TRI (Chemical Tracking):** Regulators enforce tight restrictions on per- and polyfluoroalkyl Substances (PFAS), requiring factories to log strict full material declarations (FMDs) and updated safety data sheets to control toxic chemical accumulation.
- **ISO 14001 (Environmental Management):** Dictates how fabs monitor, manage, and reduce their ecological footprint, explicitly covering massive cleanroom energy demands and toxic chemical wastewater recycling.

- **ISA/IEC 62443 (Operational Cyber-Physical Safety):** Governs industrial automation control systems. It protects fab machinery from external cyber interference that could result in structural physical hazards, tool explosions, or cleanroom gas leaks.
- **OSHA Semiconductor Overview:** Provides comprehensive regulatory resources, standards, and safety fact sheets for cleanroom environments.
- **IEC / EHS Guidelines:** The World Bank Group's Environmental, Health, and Safety guidelines detail pollution prevention and hazard abatement techniques.
- **NFPA 318 Standard:** The standard for the protection of semiconductor fabrication facilities, addressing fire prevention and hazardous production materials.

### 6.2.2 Hardware Functional Safety Standards

These frameworks mandate specific engineering methodologies, design redundancies, and diagnostic coverages to guarantee chips operate safely within mission-critical infrastructure:

- **ISO 26262 (Automotive Semiconductor Safety):** The gold standard for road vehicle electronics. Part 11 of this standard outlines exact metrics for semiconductor design. It defines Automotive Safety Integrity Levels (ASIL A to D) based on severity, exposure frequency, and controllability. ASIL-D represents the highest level of rigor required for autonomous and steering microcontrollers.
- **IEC 61508 (The Umbrella Standard):** The foundational, cross-industry standard for any programmable electronic safety system. It introduces Safety Integrity Levels (SIL 1 to 4) to mathematically score the acceptable failure rate of a chip based on potential injury risk.
- **DO-254 / DO-178C (Aerospace & Avionics):** Governs design assurance for airborne electronic hardware. It requires absolute traceability from the silicon gate layout up to flight software to ensure cosmic rays or extreme atmospheric pressure do not trigger uncontrolled system failures.
- **IEC 62304 / ISO 14971 (Medical IC Devices):** Mandated for semiconductors embedded within life-critical health systems (e.g., pacemakers, insulin pumps). It specifies rigid hardware-software life cycles to guard against medical device crashes

India's semiconductor sector is expanding while its sector-specific EHS ecosystem is still maturing. The Occupational Safety, Health and Working Conditions Code, 2020 provides a broad framework for workplace safety and health. However, semiconductor manufacturing requires more specialized controls than general factory compliance alone. Facilities should also align with hazardous chemical management, factory licensing, environmental permissions, fire approvals, disaster management planning, and state-level rules. The India Semiconductor Mission and related investments indicate that EHS guidance for fabs is still evolving. This creates an opportunity: India can design semiconductor safety systems proactively rather than reactively. New facilities should embed international best practices at the design stage, including safety-by-design, tool certification, gas monitoring architecture, emergency response planning, and occupational exposure databases.

### 6.3 Recommended Safety Best Practice Framework for India

A practical Indian semiconductor EHS framework should include the following:

1. **Design-stage EHS review:** Hazard identification should begin during fab site selection, plant layout, tool procurement, and gas farm design.
2. **Process hazard analysis:** Use HAZOP, what-if analysis, failure mode analysis, and layer-of-protection analysis for gas, chemical, and exhaust systems.
3. **Chemical governance:** Maintain a centralized chemical approval process, SDS review, exposure limits, substitution review, and inventory tracking.
4. **Engineering controls:** Prioritize closed systems, exhaust ventilation, scrubbers, gas cabinets, leak detection, interlocks, and emergency shutdown systems.
5. **Emergency preparedness:** Prepare for HF exposure, gas leaks, solvent fires, chemical spills, toxic releases, cleanroom evacuation, and mass casualty scenarios.
6. **Medical surveillance:** Conduct pre-placement exams, periodic health checks, biological monitoring where appropriate, reproductive health counseling, and long-term exposure records.

7. **Contractor safety:** Include tool vendors, maintenance contractors, construction workers, chemical suppliers, and waste handlers in the same EHS system.
8. **Training and competency:** Provide role-based training for operators, engineers, maintenance teams, emergency teams, contractors, and managers.
9. **Worker participation:** Establish safety committees, near-miss reporting, stop-work authority, and anonymous concern reporting.
10. **Data transparency:** Track exposure results, incidents, near misses, corrective actions, medical surveillance trends, and audit findings.
11. **Compliance integration:** Align Indian legal compliance with ISO45001, ISO14001, SEMI S2, and global customer audit expectations.
12. **Local emergency coordination:** Train local fire services, hospitals, ambulance teams, and district authorities on semiconductor-specific hazards.

#### 6.4 Risk Management Measures (RMMs)

Because of a number of guidelines created by Semiconductor Equipment and Materials International (SEMI) and cooperation between suppliers of chemicals and process tools and semiconductor manufacturers, the semiconductor industry has implemented risk mitigation measures that frequently surpass regulatory requirements. Table 1 displays this.

**Table 1. Risk Mitigation Measures**

|                                               | Control Measures for Safe Use | Control Measures for Environment | Chemical Delivery/Waste Management Controls | Aqueous Solutions | Specialty Gases | Organic Compounds | Metallic Compounds |
|-----------------------------------------------|-------------------------------|----------------------------------|---------------------------------------------|-------------------|-----------------|-------------------|--------------------|
| <b>Chemical Management</b>                    |                               |                                  |                                             |                   |                 |                   |                    |
| Chemical Assessment and Selection             | ✓                             | ✓                                | ✓                                           | ✓                 | ✓               | ✓                 | ✓                  |
| Chemical Tracking and Control                 | ✓                             | ✓                                | ✓                                           | ✓                 | ✓               | ✓                 | ✓                  |
| <b>Process Level Controls</b>                 |                               |                                  |                                             |                   |                 |                   |                    |
| Robotic Wafer Transport and Handling          | ✓                             | ✓                                |                                             |                   |                 |                   |                    |
| Bulk Chemical Delivery Systems                | ✓                             | ✓                                | ✓                                           | ✓                 |                 | ✓                 |                    |
| Automated Gas Management and Delivery         | ✓                             | ✓                                | ✓                                           |                   | ✓               |                   | ✓                  |
| Automated Spill Control and Leak Sensors      | ✓                             | ✓                                |                                             | ✓                 | ✓               | ✓                 | ✓                  |
| Safety Interlocks and Energy Isolation        | ✓                             |                                  |                                             |                   |                 |                   |                    |
| Totally Enclosed Process with Exhaust         | ✓                             | ✓                                | ✓                                           | ✓                 | ✓               | ✓                 | ✓                  |
| Exhaust Management                            | ✓                             | ✓                                | ✓                                           |                   |                 |                   |                    |
| Integrated Fire Protection Systems            | ✓                             | ✓                                |                                             | ✓                 | ✓               | ✓                 | ✓                  |
| <b>Gas Management</b>                         |                               |                                  |                                             |                   |                 |                   |                    |
| Sub-atmospheric Gas Sources                   | ✓                             | ✓                                |                                             |                   |                 |                   | ✓                  |
| Specially Designed Gas Cabinets/Manifolds     |                               |                                  |                                             |                   |                 |                   |                    |
| • Auto leak detection, flow control, shut-off | ✓                             | ✓                                |                                             |                   | ✓               |                   | ✓                  |
| • Remote gas storage                          |                               |                                  |                                             |                   |                 |                   |                    |
| • Auto-purge gas lines                        |                               |                                  |                                             |                   |                 |                   |                    |
| • Integrated fire safety systems              |                               |                                  |                                             |                   |                 |                   |                    |
| Delivery Containment Systems                  | ✓                             | ✓                                | ✓                                           |                   | ✓               |                   | ✓                  |

| Liquid Chemical Delivery                                 |   |   |   |   |   |   |   |
|----------------------------------------------------------|---|---|---|---|---|---|---|
| Bulk Chemical Delivery Systems                           | ✓ | ✓ |   | ✓ |   | ✓ |   |
| Automated Spill Control and Leak Sensors                 | ✓ | ✓ |   | ✓ |   | ✓ | ✓ |
| Delivery Containment Systems                             | ✓ | ✓ | ✓ | ✓ |   | ✓ | ✓ |
| Liquid/Solid Waste Management                            |   |   |   |   |   |   |   |
| Corrosive Neutralization Systems                         |   | ✓ | ✓ | ✓ |   |   | ✓ |
| Solvent Collection Systems                               |   | ✓ | ✓ |   |   | ✓ |   |
| Metal Collection Systems                                 |   | ✓ | ✓ | ✓ |   |   | ✓ |
| Recycle/Reclaim Procedures                               | ✓ | ✓ | ✓ | ✓ |   | ✓ |   |
| Emissions Management                                     |   |   |   |   |   |   |   |
| Point of Use Abatement Systems                           | ✓ | ✓ |   |   | ✓ |   | ✓ |
| Central Abatement Systems                                |   | ✓ |   | ✓ | ✓ | ✓ | ✓ |
| Special Protective Measures                              |   |   |   |   |   |   |   |
| Environmental & Safety Management Systems and Procedures | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Employee ESH Training                                    | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Personal Protective Equipment                            | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Emergency Response Teams                                 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Building Chemical Storage Containment Systems            | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |   |
| Building Fire Suppression Systems                        | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Maintenance Hazardous Materials Purge Systems            | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

## 6.5 Future Research

In India, future studies should concentrate on:

1. Establishing an occupational exposure registry for semiconductors nationwide.
2. Creating job-exposure matrices for OSAT and Indian factories.
3. Create PFAS regulations that are risk-based and do not limit chip manufacturing.
4. Encourage R&D initiatives to hasten the development of effective PFAS substitutes and environmental controls. For the majority of the more than 1,000+ semiconductor manufacturing applications, there are no known substitute substitutes for PFAS due to its many unique characteristics.
5. Examining contract and maintenance workers' exposure to chemicals.
6. Assessing outcomes related to cancer, respiratory, neurological, dermatological, and reproductive systems.
7. Evaluating weariness, shift work, and psychological stress in cleanroom settings.
8. Creating emergency response plans tailored to India for solvent, silane, phosphine, arsine, and HF incidents.
9. Comparing safety culture across domestic and multinational semiconductor facilities.
10. Evaluating whether imported global EHS standards are effectively implemented in Indian subcontracting and construction contexts.
11. Studying nanomaterial and advanced packaging hazards.
12. Creating public-private EHS training programs for regulators, hospitals, and emergency responders.

## 7. CONCLUSION

India has a significant industrial opportunity in semiconductor manufacturing, but without developing occupational health and safety systems at the same rate as production capacity, it can present complex hazards from chemicals, specialty gases, cleanroom work, high-energy tools, ergonomic stressors, shift work, and waste handling. Gaps in exposure knowledge, chemical transparency, and long-term worker health surveillance persist in international semiconductor literature. India has a good legal foundation in its OSH Code, but semiconductor facilities need sector-specific controls including process safety management, gas detection, chemical governance, medical surveillance, contractor safety, and emergency preparedness. India should prevent by design: build fabs and OSAT facilities with world-class EHS systems from the beginning, not after incidents happen.

Governments take a more focused and multi-faceted approach to tackling PFAS concerns. Protecting human health and the environment, this vital industry will continue to prosper by collaborating and innovating. Advocate for PFAS legislation and regulations that give authorities the ability to conduct risk-based analysis and controls on emissions and the ability to access chemicals vital to the production of semiconductors. Any policy should take into consideration the reality that there is no foreseeable way to develop an alternative to PFAS for critical applications in the semiconductor industry within decades. Advocate for R&D programs that draw on industry and academic expertise to improve detection, monitoring, control, and abatement; to explore alternatives to PFAS; and to address technical hurdles in developing and deploying alternative materials and manufacturing

processes.

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