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Review article

Silent threats, smart surveillance: modernizing toxicovigilance for invisible chemical exposures- a review

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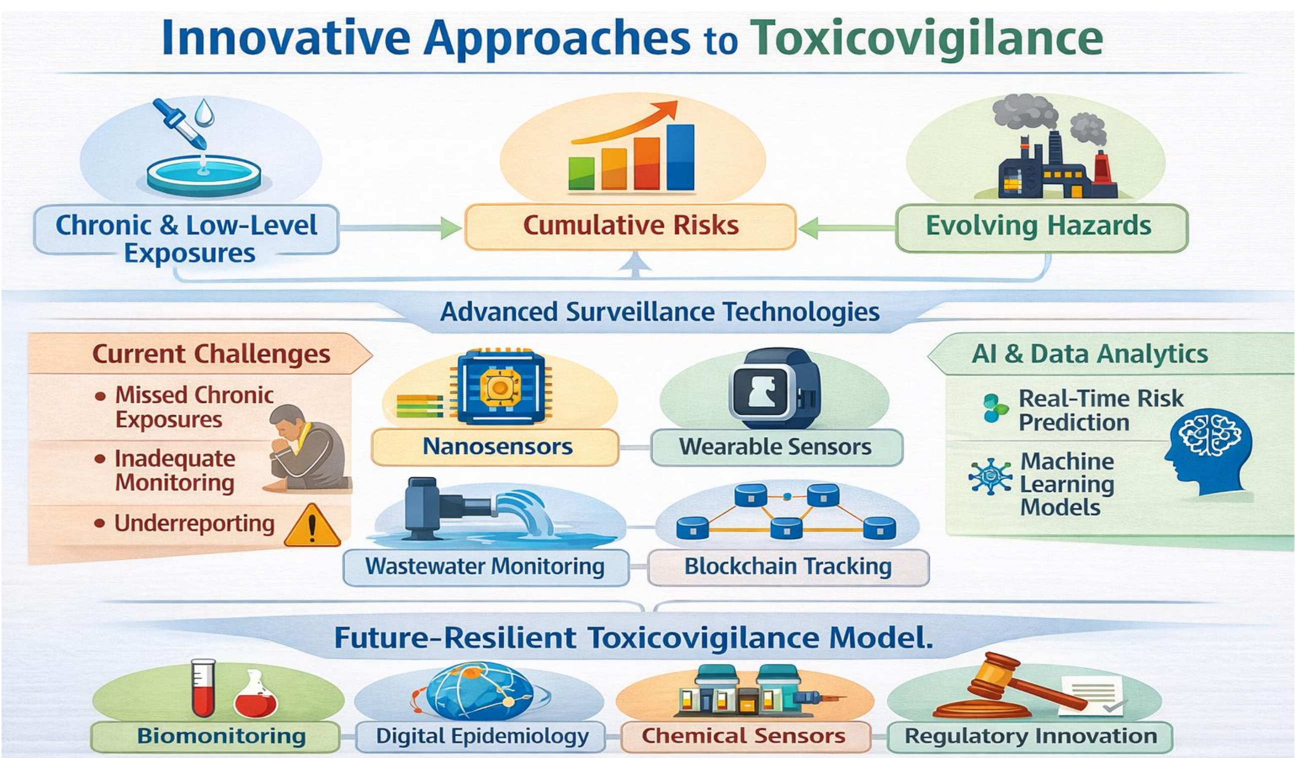
ABSTRACT

The conventional toxicovigilance systems, which mainly focus on acute and overt poisoning, may fail to identify chronic and low level and cumulative exposures that play a part in disease burden over the long run.



The new technology of exposure science, biomonitoring, digital epidemiology, and AI-enabled environmental surveillance all provide new avenues to innovate toxicovigilance. In this review, the changing environment of chemical exposures in the environmental, occupational, and consumer settings is analysed, with gaps in the existing detection and reporting systems. It also discusses future technologies of surveillance, such as nanosensors, wearable exposure sensors, wastewater sensors, chemical sensors tracked using blockchain technology, and machine-learning algorithms to predict risks in real-time. This article offers a future-resilient model of toxicovigilance through scientific, technological, and regulatory innovation, which would solve the issue of the silent but widespread toxic hazard of invisible chemical exposures.

Keywords: Toxicovigilance, Environmental toxins, AI surveillance, Occupational toxicology, Smart sensors, Digital epidemiology.

INTRODUCTION

Toxicovigilance was traditionally defined as the systematic observation, identification, and assessment of the toxic hazards of human health, it has been one of the foundations of the protection of population health. Traditionally, the toxicovigilance systems were designed based on acute poisoning, pesticide ingestion, industrial accidents, medication overdoses, and household chemical exposures. But the worldwide chemical landscape has changed radically, and it has produced an even more challenging issue, which is invisible, chronic, and low-dose exposures that silently become accumulated within individuals and communities. Such exposures are due to new industrial compounds, synthetic chemicals, microplastics, endocrine-disrupting substances, consumer product additives, and indoor pollutant substances that are often not noticed but are found in biological and environmental systems [1]. This review, to the best of our knowledge, is one of the initial attempts to move toxicovigilance beyond the primarily reactive poisoning surveillance model and reposition it as a predictive, technology-based public health intelligence system focused on the unnoticed, chronic, and cumulative chemical exposures.

The concept of toxicovigilance

The current toxicovigilance is no longer just about registering cases of poisoning. It also includes a proactive and multi-layered surveillance system that focuses on the recognition of initial indicators of chemical damage, the evaluation of exposure routes, the definition of the vulnerabilities of the population at large, and the guidance of preventive measures. Such growth is necessary since most of the modern exposures no longer arise as direct clinical poisonings but rather lead to the emergence of chronic illnesses like cancer, neurodevelopmental disorders, and dysfunction of the metabolic system and reproductive abnormalities. Therefore, toxicovigilance ceases to be a reactive science; it is becoming a predictive and proactive science [2] .

The invisible chemical exposures that are growing

The exposures of the present day are complex and in many ways covert: indoor air pollution based on volatile organic compounds, off-gassing plastics, contaminated food packaging, work-related nano-materials, chemicals of personal care products, and redistribution of pollutants due to climate. Since these exposures are diffuse, intermittent as well as cumulative, they often remain unseen by the traditional surveillance systems [3].

The reason behind modernizing toxicovigilance

The traditional toxicovigilance systems based on clinical reporting, poison control studies and laboratory-verified cases are not suitable in identifying low-level or chronic chemical exposures. To modernize these systems, the inclusion of real-time environmental, occupational and consumer exposure data, digital epidemiology and AI to formulate emerging threats and earlier biological indicators before illness occurs are necessary. The combined efforts of these innovations enhance regulatory rulings and add value to monitoring the new and untested chemicals [4].

Scope and objectives

This review attempts to analyse the changing environment of the invisible chemical exposures, find shortcomings in classical toxicovigilance paradigms, discuss new surveillance technologies in the 21st century, such as artificial intelligence, smart sensors, and so-called digital spaces, and suggest a new model of toxicovigilance that should be based on modernity and be integrated. This article is a synthesis of scientific, technological, and policy understanding of the fact that strong, proactive toxicovigilance systems are an urgent necessity to allow communities to protect themselves in regards to silent and widespread risks that are caused by chemicals [5]. The most remarkable aspect of this work is its holistic integration of exposomics, artificial intelligence, smart sensing technologies, digital epidemiology, and regulatory innovation into one single and future-proof toxicovigilance framework.

The changing scene of exposure to chemicals

The human interaction with chemicals has been changing in terms of scale, variety, and complexity in the last twenty years. In contrast to the older periods of time when high-dose and very evident toxic exposures prevailed, contemporary exposures are more characterised by chronic, low-dose and sometimes invisible chemical exposures. Such exposures happen in environmental, occupational, domestic, and consumer sectors and generate a diffuse but diffuse effect on population health [6].

Table 1 describes the categorization of the chemical exposures based on the source of exposure, length of exposure, exposure pathway and population at risk, which provides a systemic approach to perceiving the various patterns of exposure in toxicovigilance.

Table 1: Classification of Chemical Exposures

Category	Source	Examples	Associated Health Risks
Environmental	Air, water, soil, climate-related redistribution	PFAS, heavy metals (lead, mercury), dioxins, microplastics	Cancer, neurotoxicity, endocrine disruption, reproductive disorders
Occupational	Industrial processes, manufacturing, agriculture, mining	Solvents, pesticides, nanoparticles	Respiratory diseases, dermal toxicity, chronic organ damage, neurological effects
Consumer Products	Food packaging, cosmetics, personal care products, household chemicals	BPA, parabens, synthetic fragrances, phthalates	Endocrine disruption, metabolic disorders, reproductive toxicity
Indoor / Built Environment	Furniture, building materials, cleaning agents, indoor air	VOCs, formaldehyde, flame retardants, off-gassing plastics	Allergies, asthma, respiratory irritation, chronic low-dose toxicity
New / Novel Chemicals	Advanced materials, nanomaterials, new synthetic additives	Nanoparticles, engineered nanomaterials, new pesticides	Unknown or poorly characterized long-term effects, bioaccumulation, subtle biochemical perturbations

New environmental and industry pollutants

The fast industrialisation process, urbanisation, and growing chemical production have brought to the environment thousands of new compounds, many of which do not have a full toxicological profile. A set of new contaminants (such as persistent organic pollutants (POPs) and per- and polyfluoroalkyl substances (PFAS), flame retardants, microplastics, and nanomaterials) can remain in the food web and accumulate in the tissues of humans. Among the factors that have led to the increased soil, water and air pollution are emissions of industrial wastes, urban run-offs and air pollution [7].

Exposures to indoor, occupational, and built-environment

Household settings where people are exposed to up to 90% of their time have become significant contributors of the invisible chemical exposures [8]. In workplaces, the solvents, heavy metals, pesticides, nanomaterials and manufacturing by-products are also an extra source of hazards to the workers. The development of e-waste recycling plants on a large scale in low-resource environments puts workers into contact with complex blends of toxicants with little to no protective measures [9].

Consumer products, food contaminants, and exposures by lifestyle

Among the consumer goods that pose a significant contribution to the chemical burden that people have to bear in their daily lives, one can mention consumer goods like cosmetics and personal care products, electronics and packaged foods. The substances that are referred to as endocrine-disrupting chemicals (EDCs) comprise parabens, bisphenol A (BPA), and phthalates, which are found in plastics, cosmetics, and food packaging. The use of pesticides, food additives, microplastics, and contamination from the environment are all factors that come from the modern production and agriculture and that invade the food chain [10].

New exposure pathways and climate change

Climate change presents new exposure paths as the world's temperatures increase. Heat increases chemical volatilisation, hence high concentrations of pollutants are present in the air. The spillage can relocate the industrial chemicals, heavy metals and sewage wastes within the residential places. The toxic smoke produced by wild fires contains dioxins, particulates and synthetic chemical by-products. Also, disturbed ecosystems enhance degradation or conversion of chemicals into other forms which may be more toxic. The dynamics ensure that the toxicovigilance systems have to continuously adjust to the dynamics of the environment [11].

Weaknesses of the conventional toxicovigilance systems:

Although these systems of traditional toxicovigilance have been in operation long to protect the health of the population, they were largely intended to identify the occurrence of acute, symptomatic, and clinically identifiable poisoning incidents. Due to changing patterns of chemical exposure to low-dose, chronic and mixed exposures, these old systems are no longer well able to detect and discern subtle toxicological signals. There are a number of structural, methodological, and operational shortcomings that make them unable to identify chemical threats that are invisible [12]. Table 2 provides a summary of the major weaknesses of established toxicovigilance systems, which include a lack of early detection, clinical reporting, data fragmentation, and a lack of chronic exposures to low doses.

Underreporting and diagnostic uncertainty

The traditional toxicovigilance uses, to a large extent, clinical reporting of health institutions and poison control centres. Nevertheless, acute symptoms are not manifested in the majority of individuals who experience low-level chemical exposures, which leads to severe underreporting. Most of the health impacts include endocrine interference and metabolic, delay in development or slight neurobehavioral alterations, which cannot be easily attributed to chemical exposure [13]. Diagnostic uncertainty and misclassification, clinicians usually do not have the training, resources, or diagnostic tools to detect exposure-related illnesses. Consequently, surveillance mechanisms record only a small proportion of events of exposure.

Hurdles in the process of identifying low-level and chronic exposures

Conventional systems are geared towards single-agent toxicities as opposed to complex mixtures and chronic micro exposures that are usually experienced in contemporary settings. The low dose exposures tend to work below the toxicological doses of risk assessments that are classical. In addition, a long latency period between exposure and disease apparent in carcinogenesis, endocrine diseases and neurodegeneration makes them difficult to track [14]. Current biomonitoring programs, where they exist, are not comprehensive in scope and coverage of the population, which results in significant gaps in the data about cumulative exposure in stages of the lifetime. Most chemicals in modern times e.g. PFAS and nanomaterials do not have any biomarkers or standard laboratory tests, which makes them hard to detect.

Table 2: Limitations of Traditional Toxicovigilance Systems

Limitation	Description	Effect on Public Health
Underreporting & Diagnostic Gaps	Depending on clinical cases and poison centre reports; a significant portion of low-dose and chronic exposures are not detected at all	Late identification of chemical hazards; incomplete epidemiology information.
Poor Detection of Low dose and chronic exposure	Traditional systems give emphasis on acute, high-dose toxicity; chronic and mixture exposures are frequently overlooked	Inability to detect long-term or subtle health effects, e.g., endocrine disruption or neurodevelopmental disorders
Isolated Data Systems System	Environmental, occupational, clinical, and industrial data systems are often separate entities with little integration	Hinders comprehensive risk assessment and timely response to emerging threats
Delayed Response Mechanisms	Passive reporting systems delay the identification of the problem; the absence of real-time monitoring	Increases population exposure before interventions are implemented
Regulatory and Policy Gaps	Outdated regulations and incomplete chemical testing; slow updates on permissible limits	Weak enforcement, inadequate protection for vulnerable populations
Limited Public Awareness	Communities may be unaware of exposure risks or early warning signs	Reduced preventive actions and delayed community engagement in exposure mitigation

Disaggregated data systems and sluggish response systems

The data of toxicovigilance are usually stored in separate systems emergency room records, poison centre databases, occupational health registries, environmental monitoring networks and industrial chemical inventories. Such datasets hardly combine and create disjointed insights and slow interpretation of emerging threats. Conventional surveillance is often passive in nature and activated by the appearance of clinical notifications and not by active monitoring of the environment or of biological parameters. There is also the constraint of the inability to identify early red flags due to the absence of real-time data analytics or predictive modelling. This delay has the ability to enable harmful exposures to last for years in communities before any intervention is done [15].

Policy, regulation, and public awareness gaps

The adoption of obsolete regulatory frameworks is a major limitation to toxicovigilance. Numerous new chemicals are introduced in the market without thorough toxicological testing, and regulatory scrutiny processes are slow, reactive or constrained by a lack of evidence. Most of the regions do not require industries to report complete chemical inventories or publication of trace emissions. There is minimal awareness among the people on the invisible chemical danger, and the community may be unaware of the early warning signs [16].

Possible future strategies in the field of modern toxicovigilance

The change of acute and visible toxic exposures to tense and chronic, as well as mixed chemical threats, requires a change in the way toxic vigilance is conducted. It is necessary to integrate real-time tracking, predictive analytics, digital surveillance, and multi-source data into modern systems to identify early indicators of harm before they emerge as crises in the field of health. New technologies, including biomonitoring inventions or AI-based models, are very promising to transform toxicovigilance and deal with the shortcomings of conventional models [17].

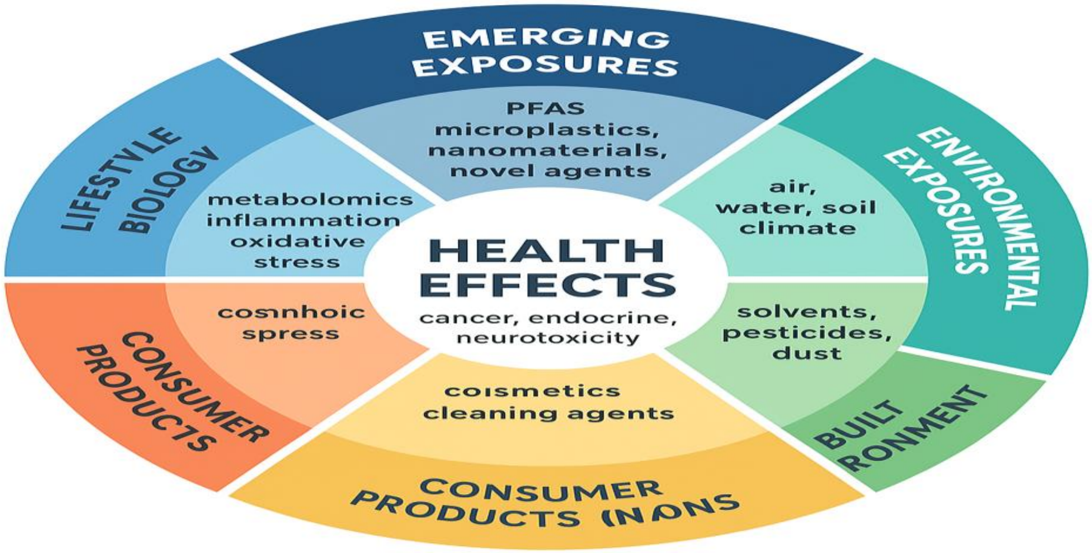
Next-Generation biomonitoring and metabolomics

Modern biomonitoring extends well beyond measurement of known substances, and high-resolution mass spectrometry, multi-omics and exposomics platforms are now used to identify thousands of chemicals, metabolites and exposure-related biomarkers simultaneously. These technologies can be used to screen emerging chemicals non-targetedly, identify biological changes in their initial stages before clinical manifestations and create exposure fingerprints correlating chemical mixes with disease pathways. Metabolomics and lipidomics also indicate small biochemical imbalances of endocrine dysfunction, oxidative stress, and inflammation [18]. Figure 1 depicts the exposome wheel, which inter-profiles the inter-relationships of the environmental, occupational, consumer, lifestyle, built-environment, and emerging chemical exposures, which together have cumulative impacts on the internal biological responses and lead to the long-term health consequences.

Environment and wearable smart sensors

A new type of innovation in the field of toxicovigilance is smart sensors, where portable and wearable sensors have the ability to measure VOCs, heavy metallographic particulates, ozone, nitrogen dioxide, pesticide residues, and nanoparticles. The community-deployed sensors are low-cost and form dense monitoring networks that record real-time spatiotemporal exposure changes, and the smartphone-based integration enables the transmission of data in real-time and the geo-tagging and personal exposure tracking. Occupational sensors and AI sensors in badges give real-time warnings and automated safety measures. These technologies, unfortunately, make exposure monitoring more democratic, giving individuals, workers and health authorities the power to take action [19].

Figure 1: Exposome wheel for invisible chemical exposures



Digital epidemiology and live surveillance systems

Digital epidemiology uses search trends on online data sources, social media conversations, community-built reporting applications, and mobile health applications in identifying developing toxic exposures or health anomalies. These tools can be used together with environmental data streams to early identify clusters that are associated with chemical releases or events of contamination. Data on sensors, health records, wastewater systems, and laboratories are combined in cloud-based toxicovigilance dashboards to provide the continuous monitoring of chemical risk indicators. The AI algorithms can scan such datasets and monitor any abnormality and provide automatic warnings to facilitate timely response and counteractions [20].

Artificial intelligence, machine learning, and predictive exposure modelling

Modernisation of toxicovigilance through Artificial Intelligence (AI) is the potential of machine learning to predict chemical toxicity, define the high-risk populations, integrate chemical catalogues with environmental measurements, and model exposure situations to give early warnings. Deep learning systems process images of satellites, sensor networks and climate data to predict areas of pollutant dispersion and exposure hot spots and predictive toxicology platforms assist regulators to prioritise chemicals before laboratory testing. Anomaly detection based on AI also helps to enhance surveillance, where slight irregularities in human or other environmental data are detected, which may indicate a toxic exposure [21].

Surveillance of wastewater and community exposure mapping

Wastewater-based epidemiology is a relatively new technology that has its initial applications in infectious disease and drug monitoring, but is now arising as an alternative, formidable instrument of chemical exposure surveillance. The biomarkers of the environment and industrial chemical exposure, pharmaceuticals, pesticides, and microplastics are found in the wastewater streams. Through the analysis of wastewater on the neighbourhood or city levels, the authorities can track the exposure patterns within the population anonymously and economically [22].

Toxicovigilance strengthening with the help of an integrated data system

The emerging trend in modern toxicovigilance is the capacity to combine the various datasets that account on the environmental, occupational, biological, and socio-behavioural aspects of chemical exposure. A discontinuous data environment in which environmental surveillance, clinical data, industrial stockpiles and population health documents are independent is still one of the most considerable obstacles to proactive toxicovigilance. Enhancing the data integration will allow identifying the chemical threats early, contributing to the rapid response and improving regulatory decision-making [23]. Table 3 shows the integrated data systems and digital tools that make toxicovigilance more efficient in terms of providing data aggregation in real-time, cross-sector interoperability and advanced analytics to help detect exposures in time.

Databases of exposure and analysis of big data

Big data analytics provides the computer capacity to compute and analyse complex exposure data of large populations and settings. It is possible to connect exposure databases, e.g., chemical registries, biomonitoring outcomes, pollutant emission inventories and environmental sensor networks to form an integrated surveillance ecosystem [24]. These multi-layer datasets are analysed by machine-learning algorithms to spot emerging patterns, exposure-response associations and anomalies that otherwise would not have been noticed. They also help in the assessment of cumulative exposures and mixture toxicology domains where the conventional toxicology tools fail. By creating national and regional exposure databases, transparency is enhanced, health research is supported, and evidence-based policy in the field of public health is educated [25].

Table 3: Integrated data systems and tools

System	Function	Application in Toxicovigilance
Cloud-Based Data Hubs	Centralised storage and real-time integration of environmental, clinical, occupational, and industrial data	Enables cross-sector analysis, trend monitoring, and early warning generation
Blockchain Platforms	Recent and transparent chemical supply chains and emissions tracking	Guarantees transparency and traceability, regulation, and quick response in cases of contamination.
AI & Machine Learning systems	Predictive modelling, anomaly detection, and chemical risk prediction through QSAR	Assists in decision-making, identifies emerging hazards, and prioritises high-risk chemicals.
Geographic Information Systems (GIS)	Mapping of chemical exposures, population vulnerability, and environmental information	Facilitates community exposure mapping, hotspot identification, and resource allocation
Digital Epidemiology Tools	Mobile apps, online reporting systems, and social media monitoring	Early detection of exposure clusters and public health signal identification
Laboratory Information Management Systems (LIMS)	Streamlined collection, storage, and analysis of biomonitoring and toxicology data	Enhances data accuracy, standardisation, and cross-study integration
IoT Sensor Networks	Real-time environmental and occupational monitoring	Continuous detection of chemical exposures across diverse settings

Inter-sectoral interrelations: health, environment, and industry

Toxicovigilance needs to be done collaboratively, not only among health agencies, but also with environmental regulators, the industry, occupational safety departments, and the health institutions of the population. Exchange of chemical inventories, emissions, clinical reports, and environmental monitoring outcomes can be used to identify source of exposure in a faster manner, help in assessing the risk, interact with regulatory response, and communication within the stakeholders. The development of common surveillance systems or data centers improves interoperability and minimizes information gaps and gives a more realistic picture of exposure dynamics among communities and workplaces [26].

Early warning systems and communication of risk

Close coordination of the data systems facilitates early warning systems where the environmental and biological data is automatically processed to identify any potential environmental threat. Such systems are a combination of sensor-related information, epidemiological trends, satellite imagery, and records of industrial activities that can result in alerts of abnormal exposure trends. These signals must be translated into action by the people and to do so proper communication risk strategies are necessary. Live notifications, mobile notifications so citizens can act, and platforms that allow individuals to engage with communities enable them to react to any potential threat, preventive behaviours, and require regulators to be accountable. The open communication also enhances the confidence of the population and encourages the community to engage in exposure monitoring [27].

Ethical, regulatory and policy consideration

With the development of toxicovigilance systems to incorporate improved sensors, AI-based analytics, and data networks with capabilities to interact, their implementation presents significant ethical, regulatory, and policy issues. It is important to achieve responsible implementation to ensure that people will not lose their trust, that their personal privacy is not compromised, and that their administration is transparent. The considerations are critical in ensuring that toxicovigilance is updated to ensure that the values of society and welfare of the people are safeguarded [28]. Table 4 presents the most important regulatory and ethical frameworks to toxicovigilance focusing on standards of data governance, risk assessment, transparency to the population, and responsible use of emerging surveillance technologies.

Table 4: Regulatory and Ethical Frameworks

Area	Key Issues	Proposed Solutions
Regulatory Oversight of Emerging Chemicals	Restricted pre-market testing, obsolete exposure limits, and inadequate evaluation of mixtures and low-dose effects.	Compulsory safety evaluations for new chemicals; constant renewal of exposure limits with the help of biomonitoring data; AI-supported toxicity forecasting tools.
Data Privacy & Consent	The use of sensors and digital tools for continuous monitoring poses a risk of unauthorised data capture, and there remains a lack of clarity regarding the ownership of the data related to exposure and health.	On the other hand, if strong data protection laws, transparent consent processes, anonymisation and encryption standards, and community governance mechanisms are in place, the situation could be quite different.
Cross-Sector Coordination	Fragmented communication between environmental, health, industrial, and occupational agencies	Integrated regulatory platforms; routine data sharing; unified national toxicovigilance policies
Equity & Non-Discrimination	The marginalised communities would be subjected to disproportionately high surveillance, and their exposure data could be misused by employers or insurers.	The imposition of equity-centred policies, anti-discrimination measures, and community involvement in the planning of surveillance would be the means of combating this issue.
Global Harmonization	Variability in chemical regulations across countries; inconsistent reporting requirements	Alignment with the WHO, IPCS, Stockholm and Rotterdam Conventions; standardised biomonitoring protocols; cross-border data exchange
Ethical Use of AI	Bias in predictive models; lack of transparency in algorithmic decision-making	Ethical AI frameworks, auditability of models, explainable AI systems, and diverse datasets for training

Data confidentiality and ethical smart surveillance

Next-generation toxicovigilance relies on massive environmental, occupational, biological and digital data gathering, but wearable sensors, mobile applications and AI platforms are able to gather sensitive personal data, which poses ethical issues of privacy, consent, data ownership, possible abuse, and unjust surveillance. Smart surveillance systems require strong data-governance systems to support anonymisation, encryption, and use under the purpose of public health only and are complemented by the transparent consent process, fair policies, and community participation that would build trust in the smart surveillance system [29].

Modernisation of regulations on the emergent chemicals

Most of the modern chemicals, such as nanomaterials, PFAS, endocrine disruptors, and artificial additives, are introduced into commercial practice with little or no toxicological evaluation, and the existing regulations usually follow scientific progress and do not cover long-term, low-dose, or mixture exposures. The contemporary regulatory frameworks need to implement the proactive measures, including the requirement of pre-market safety testing, integration of AI-predicted toxicological profiles in the risk assessment, revision of the allowed exposure limits, rooted in real-life biomonitoring, and the introduction of transparent reporting of chemical stocks and exposures. It is also important that regulations of various countries be harmonised globally, as chemical production and distribution are transnational [30].

Community involvement and openness

Toxicovigilance requires good collaboration with communities. Community involvement improves the accuracy of data, covers a greater area under surveillance as well and enhances the response strategies. Openness in sharing exposure risks, be it by dashboard, mobile alerts, and local advisory boards, enables people to act preventively. Citizen science initiatives (e.g. community air-quality monitoring) can also be implemented to augment formal surveillance and react to problems at the level of regulation. It would need to ensure that the decision-making process would take into consideration the marginalised and the high-risk population to offer similar security to individuals concerning their health [31].

CONCLUSION

The issue of invisible chemical exposures has turned out to be one of the most widespread and least regarded public health issues of the 21st century. With the ever-present pollution with industrial toxins, consumer-product chemicals, microplastics, and climate-induced contaminants, the traditional toxicovigilance frameworks used in cases of acute and symptomatic poisonings are inadequate to ensure human health safety. The move toward low-dose, chronic and mixture exposures require a progressive surveillance methodology that is receptive to technological development, data assimilation and engagement.

The future of toxicovigilance, enabled by novel biomonitoring, wearable health sensors, artificial intelligence, and digital epidemiology, presents the biggest potential of offering early warning signs of damage before the onset of poor health. The combination of these innovations with the coordinated data systems, the open governance systems, and the innovative regulations will enhance the strength of the ability to detect risks, lead interventions, and safeguard vulnerable groups. Such moral issues as data privacy, community involvement, and fair access should be the main focus of the integration of these technologies, so as to make responsible and trustworthy surveillance. Existing toxicovigilance models are focused primarily on the event of occurrence and are mainly retrospective. This shift, in particular, is to direct the focus on the development of a preventive alert structure that possibly will pick up signals of toxicity early in order to prevent harm at the population level.

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