

Biomarkers for Occupational Chemical Exposure: A Narrative Review from Traditional Monitoring to Omics and Digital Health Applications

Chan Pattama Polyong^{1*}, Thawatchai Eksanti², Pichitra Patipat³ and Kornwika Harasarn⁴

¹Occupational Health and Safety Program, Faculty of Science and Technology, Bansomdejchaopraya Rajabhat University, Bangkok, 10600, Thailand

²Community Health Program, Faculty of Public Health, Nakhon Ratchasima Rajabhat University, Nakhon Ratchasima Province, 30000, Thailand

³Department of Industrial Hygiene and Safety, Faculty of Public Health, Burapha University, Chonburi Province, 20131, Thailand

⁴Occupational Health and Safety Program, Faculty of Public Health, Ubon Ratchathani Rajabhat University, Ubon Ratchathani Province, 34000, Thailand

* Corresponding author. E-mail address: chanpattame.po@bsru.ac.th; chan.bsru@gmail.com

Received: 29 December 2025; Revised: 6 July 2026; Accepted: 27 July 2026; Available online: 1 October 2026

Abstract

Occupational exposure to hazardous chemicals remains a major public health challenge, particularly in developing countries where regulatory enforcement and surveillance systems are limited. This review synthesizes recent advances in the application of biomarkers for assessing occupational chemical exposure and related health effects. Relevant literature published between 2015 and 2025 was identified through searches of major scientific databases, including PubMed and Google Scholar, using keywords related to occupational exposure, biomarkers, biomonitoring, omics, and digital health. Studies addressing biomarkers of exposure, effect, and susceptibility in occupational settings were reviewed and synthesized. Biomarkers of exposure, effect, and susceptibility provide direct and sensitive measures that link external exposure with internal dose and biological responses. Evidence shows strong associations between benzene exposure and hematotoxicity, organophosphate pesticides and neurotoxicity, heavy metals and renal impairment, as well as organic solvents and hepatic injury. Importantly, the usefulness of biomarkers depends on their biological half-life and the exposure window they represent, ranging from recent exposure to cumulative long-term exposure. Validation criteria such as sensitivity, specificity, reproducibility, and clinical relevance are essential to ensure analytical reliability and health risk interpretation. Emerging technologies, including omics-based molecular markers, non-invasive matrices, multi-matrix monitoring, and biosensor-driven point-of-care testing, are revolutionizing biomonitoring practices. These innovations, together with the integration of genetic and environmental data, are shaping a new era of Precision Occupational Health, enabling early intervention and individualized prevention. Furthermore, advances in wearable sensors and digital health platforms support near real-time occupational health surveillance and more proactive risk management. In conclusion, the integration of validated biomarkers into occupational health surveillance systems provides a powerful strategy to enhance chemical risk management, safeguard workers' health, and inform policy decisions globally.

Keywords: biomarkers, occupational chemical exposure, biomonitoring, occupational health surveillance, precision occupational health

Introduction

Chemical exposure remains one of the most important occupational health challenges worldwide. Workers in manufacturing, agriculture, mining, transportation, healthcare, and service industries are routinely exposed to a wide range of hazardous substances, including solvents, pesticides, heavy metals, volatile organic compounds, and emerging industrial chemicals. Despite advances in occupational safety regulations and preventive measures, hazardous chemical exposure continues to contribute substantially to occupational diseases, disability, and premature mortality, particularly in low- and middle-income countries where exposure assessment and health

surveillance systems remain limited (World Health Organization [WHO], 2021a; Murray et al., 2020). Furthermore, increasing industrial complexity, mixed chemical exposures, and individual variability in susceptibility have created additional challenges for accurately evaluating occupational health risks and implementing effective prevention strategies (Longo et al., 2021).

Accurate assessment of occupational chemical exposure is essential for effective risk management and worker protection. Traditional environmental monitoring provides valuable information regarding external exposure levels; however, environmental measurements alone may not adequately reflect the internal dose absorbed by workers or the biological responses occurring within the body (Viegas et al., 2020). Biomarkers have therefore emerged as valuable tools for linking external exposure, internal dose, early biological effects, and individual susceptibility (Longo et al., 2021). Recent advances in biomonitoring, molecular toxicology, omics technologies, and emerging analytical approaches have expanded biomarkers' potential applications in occupational health surveillance and risk assessment (Capone et al., 2024; Longo et al., 2021). Consequently, an updated synthesis of current evidence is needed to support the selection, validation, interpretation, and practical application of biomarkers for occupational chemical exposure assessment and worker health protection.

The International Labour Organization (2021) and the World Health Organization (WHO) report that occupational diseases associated with chemical exposures, such as respiratory disorders, cancers induced by mutagens, benzene-related aplastic anemia, and hepato-nephrotoxicity from heavy metals continue to increase despite more stringent legal and safety measures (International Labour Organization, 2021; WHO, 2021a). Complex factors, including suboptimal work environments, simultaneous exposure to multiple agents, and inter-individual differences in susceptibility, make risk assessment and prevention particularly challenging.

Thailand uses a wide array of chemicals, including solvents, heavy metals, pesticides, plastics, and volatile organic compounds (VOCs) across multiple sectors. Exposure is not confined to formal industry; it extends to agriculture, construction, services, and large segments of the informal workforce (Hughes et al., 2021; Saphamrer & Hongsibsong, 2014). Consequently, chemical exposure has become a persistent public health burden, contributing to chronic illness, loss of work capacity, and rising healthcare costs.

Health effects from occupational chemical exposure span a continuum from subclinical cellular changes to chronic disease and cancer. For example, exposure to organophosphate pesticides inhibits cholinesterase activity, affecting the nervous system and potentially impairing cognition (Furlong et al., 2006). Accumulated lead in blood and bone is linked to renal and neurological dysfunction (Lanphear et al., 2018). Exposure to organic solvents has been associated with elevated liver enzymes and hepatic dysfunction among occupationally exposed workers (Umicevic et al., 2022; Polyong & Thetkatuek, 2024). Global Burden of Disease (GBD) estimates indicate that toxic occupational exposures contribute significantly to premature mortality and productivity loss, especially in low- and middle-income countries, underscoring the need for precise tools to measure and evaluate health impacts (GBD, 2020).

Biomarkers have been increasingly applied since the 1990s, but evidence from 2015–2025 has advanced substantially in sensitivity, specificity, and real-world limitations for risk assessment. Standard biomarkers such as urinary 1-hydroxypyrene for polycyclic aromatic hydrocarbons (PAHs) and urinary dialkyl phosphates for organophosphates have been repeatedly validated (Barr et al., 2004; Dalmolin et al., 2020). In parallel, emerging molecular biomarkers, e.g., DNA adducts and proteins indicative of oxidative stress, can detect preclinical changes (Brandt-Rauf et al., 2002). Interpretation, however, remains complex: results may be

influenced by ubiquitous environmental factors (diet, tobacco smoke), genetic variability, and inter-laboratory analytical differences (Angerer et al., 2018). These gaps motivate an updated synthesis to strengthen assessment and interpretation for health surveillance and to guide preventive research. Despite these advances, the growing diversity of biomarkers, emerging omics technologies, and digital health applications has created challenges in selecting, validating, and interpreting biomarkers for occupational chemical exposure assessment (Capone et al., 2024). Although occupational biomonitoring has advanced substantially, evidence remains fragmented across chemical groups, biomarker categories, and emerging technologies. A comprehensive review is therefore needed to integrate current knowledge, identify research gaps, and provide practical guidance for occupational health professionals, researchers, and policymakers. Accordingly, this review aims to comprehensively synthesize recent advances in biomarkers for occupational chemical exposure and their application in risk assessment, health surveillance, and worker protection. The review examines biomarkers of exposure, effect, and susceptibility, discusses validation criteria and practical applications, and highlights emerging technologies, including omics-based approaches, digital health tools, and Precision Occupational Health.

Content

This narrative review used a structured literature search approach. Relevant articles published between 2015 and 2025 were identified through PubMed and Google Scholar databases using combinations of keywords including “occupational exposure”, “biomonitoring”, “biomarkers”, “chemical exposure”, “occupational health”, “omics”, and “digital health”. Priority was given to peer-reviewed articles, international guidelines, and consensus documents related to occupational biomonitoring and exposure assessment. Additional references were identified through manual screening of reference lists. The retrieved literature was critically reviewed and synthesized according to major themes, including biomarkers of exposure, effect, and susceptibility, validation criteria, occupational risk assessment, health effects, emerging technologies, and future directions.

Biomarkers

The concept of biomarkers has become increasingly important in occupational toxicology because it reduces the limitations of relying solely on environmental monitoring. A biomarker is defined as a measurable biological change resulting from exposure to a chemical substance. These indicators may include parent compounds or metabolites detected in biological matrices such as blood, urine, hair, nails, or saliva, as well as biochemical or physiological changes that reflect damage to specific organs or body systems (Angerer et al., 2018; WHO, 2017).

Biomarkers serve as a direct link between exposure and health effects and can quantify both the internal dose and the body’s biological response (dose–response relationship). These functions are essential for risk assessment, occupational health surveillance, and the development of effective control measures (Sexton et al., 2004). In occupational toxicology (Fig. 1), biomarkers are generally classified into three main categories:

1. Biomarkers of Exposure

These biomarkers indicate the absorption of chemicals or their metabolites into the body and provide quantitative evidence of actual exposure. For example, blood lead level (BLL) is used to assess lead exposure among battery industry workers (Lanphear et al., 2018); urinary trans, trans-muconic acid (t, t-MA) serves

as a marker for benzene exposure (Polyong & Thetkathuek, 2024); and urinary dialkyl phosphate metabolites (DAPs) are widely used as standard biomarkers for exposure to organophosphate pesticides (Barr et al., 2004).

2. Biomarkers of Effect

These biomarkers reflect biochemical or physiological changes that indicate tissue or organ damage. For instance, elevated liver enzymes such as AST, ALT, or GGT can signal hepatic injury among workers exposed to solvents (Umicevic et al., 2022; Polyong & Thetkathuek, 2024). The micronucleus test or chromosomal aberration assays are used to identify genotoxic effects and cancer risk among workers exposed to benzene or heavy metals (Bonassi et al., 2011). In addition, inhibition of cholinesterase activity is a well-established biomarker for monitoring neurotoxicity caused by exposure to organophosphate pesticides (Furlong et al., 2006).

3. Biomarkers of Susceptibility

These biomarkers indicate individual differences in genetic or physiological characteristics that influence vulnerability to chemical toxicity. Variations in cytochrome P450 (CYP) genes, such as CYP2E1 and CYP2D6, affect the metabolism of several toxicants, including VOCs and benzene (Bolt & Thier, 2006). Polymorphisms in the GSTM1 and GSTT1 genes are associated with reduced detoxification capacity for polycyclic aromatic hydrocarbons (PAHs), increasing cancer susceptibility (Garcia-Closas et al., 2005). Likewise, variations in the paraoxonase 1 (PON1) enzyme influence individual sensitivity to organophosphate toxicity (Furlong et al., 2006). Recent genetic evidence also supports the association between PON1 polymorphisms and organophosphate sensitivity (Costa et al., 2013).

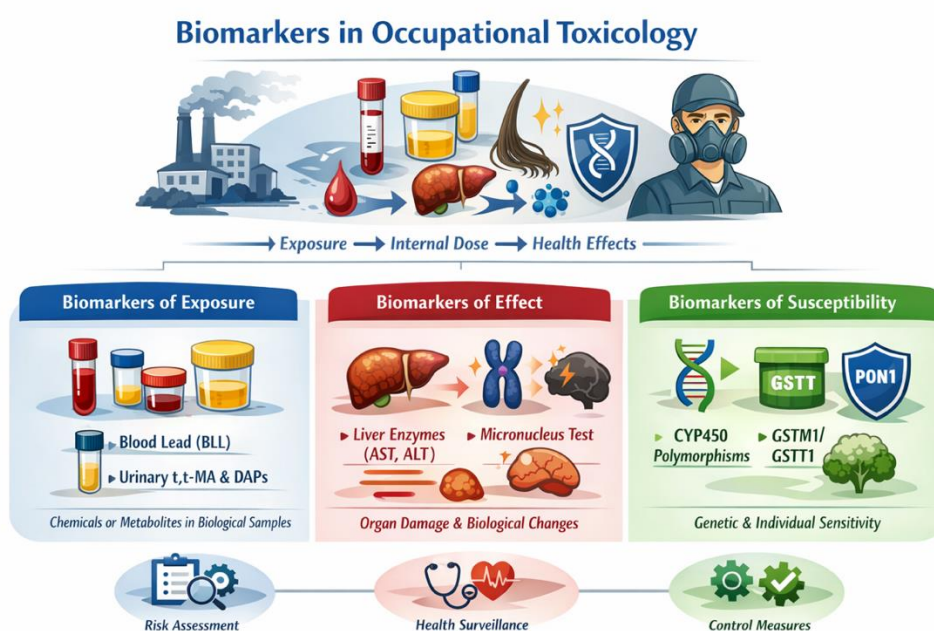


Figure 1 The concept of biomarkers in occupational toxicology

Traditional Monitoring and Biomonitoring

Occupational exposure assessment has traditionally relied on environmental monitoring, which measures the concentration of hazardous substances in workplace environments such as air, surfaces, or workplace materials. Environmental monitoring is essential for identifying sources of exposure and evaluating compliance with occupational exposure limits (OELs) (ACGIH, 2025). However, environmental measurements alone may not adequately reflect the actual internal dose absorbed by workers because individual factors such as inhalation rate,

dermal absorption, metabolism, and personal protective equipment use can substantially influence exposure levels (Viegas et al., 2020).

Biomonitoring complements environmental monitoring by measuring chemicals, metabolites, or biological responses directly in biological matrices such as blood, urine, saliva, hair, or exhaled breath. This approach provides a more accurate assessment of internal exposure and biological uptake. The selection of biological matrices and sampling time is critical because biomarker concentrations may vary according to the toxicokinetic properties and biological half-life of each chemical. An important consideration in biomonitoring is the exposure window represented by each biomarker. Biomarkers with short biological half-lives, such as urinary metabolites of solvents and pesticides, generally reflect recent exposure occurring within hours or a few days. In contrast, biomarkers such as blood lead levels, urinary cadmium, and certain DNA adducts may reflect cumulative or long-term exposure over weeks, months, or even years. Understanding the exposure window is essential for selecting appropriate biomarkers, determining optimal sampling times, and accurately interpreting biomonitoring results in occupational health practice. For example, post-shift urine samples are commonly used for assessing recent exposure to benzene and organic solvents, whereas blood lead levels may reflect cumulative exposure over longer periods.

To facilitate interpretation, biomonitoring results are often compared with established biological reference values. The American Conference of Governmental Industrial Hygienists (ACGIH, 2025) has developed Biological Exposure Indices (BEIs), which provide guidance values for evaluating occupational exposure based on biomarker concentrations. Similarly, Occupational Biomonitoring Levels (OBLs) proposed by international organizations and occupational health programs support the interpretation of biomonitoring results and risk management decisions. The integration of environmental monitoring, biomonitoring, and biological reference values offers a comprehensive framework for occupational exposure assessment and worker health protection. The comparison of traditional environmental monitoring and biomonitoring in occupational exposure assessment is shown in Table 1.

Table 1 Comparison of traditional environmental monitoring and biomonitoring in occupational exposure assessment

Aspect	Environmental Monitoring	Biomonitoring
Purpose	Measure external exposure	Measure internal dose
Sample	Air, surface, workplace materials	Blood, urine, saliva, hair
Exposure Information	Environmental concentration	Absorbed dose
Sampling Timing	During work activities	Pre-shift / Post-shift
Reference Values	OELs, TLVs	BEIs, OBLs
Advantages	Identifies exposure sources	Reflects actual uptake
Limitations	Does not account for individual variability	Influenced by metabolism and biological variability

Note: OELs, Occupational Exposure Limits; TLVs, Threshold Limit Values; BEIs, Biological Exposure Indices; OBLs, Occupational Biomonitoring Levels.

Criteria for the Validation of Biomarkers

The selection and validation of biomarkers are critical steps in accurately assessing chemical exposure and associated health effects. To ensure analytical precision and reliability, a comprehensive evaluation is required. According to recent guidance from the World Health Organization (WHO, 2017) and international expert

consensus (Apel et al., 2020; Ougier et al., 2021), a suitable biomarker should meet several key criteria as follows:

1. Sensitivity and Specificity

An effective biomarker should be capable of detecting biological changes even at low exposure levels and should specifically reflect the effects of the target substance without interference from environmental or behavioral factors. For instance, urinary dialkyl phosphate metabolites (DAPs) are widely used to assess exposure to organophosphate pesticides and have been validated for both sensitivity and specificity across diverse populations (Dalmolin et al., 2020).

2. Quantitative Relationship with Exposure (Dose–Response Relationship)

A fundamental criterion for biomarker selection is a clear quantitative relationship between biomarker levels and exposure intensity or duration, ensuring consistent interpretation. For example, blood lead levels (BLL) demonstrate a strong dose–response relationship with neurological and renal dysfunction, even at low exposure levels (Lanphear et al., 2018).

3. Technical Stability and Reliability

A reliable biomarker should yield consistent and reproducible results across laboratories using standardized analytical methods such as gas or liquid chromatography coupled with mass spectrometry (GC–MS or LC–MS/MS). The OECD and European research agencies emphasize that establishing internationally accredited laboratory standards is essential to minimize analytical variability (Apel et al., 2020). Therefore, laboratory quality should always be reported—for example, a laboratory certified under ISO 15189:2012 and approved by the Thailand Ministry of Public Health (MOPH) (Polyong & Thetkathuek, 2022).

4. Practical Feasibility

In addition to scientific accuracy, the feasibility of biomarker application must be considered—particularly in large-scale occupational surveillance. Biomarkers requiring simple and noninvasive sample collection, such as urine or blood, are preferable to those involving invasive procedures like cerebrospinal fluid sampling. This practicality facilitates implementation in field-based health surveillance programs (Hughes et al., 2021). For instance, Thailand’s Department of Disease Control recommends an initial screening of pesticide-exposed workers through structured interviews, followed by blood testing for neurochemical indicators—an approach that balances scientific validity with real-world feasibility.

5. Multi-Level Validation

Biomarker validation should cover multiple dimensions to ensure scientific rigor and generalizability: (i) Analytical validation: Assessment of accuracy, precision, sensitivity, and specificity of analytical methods, including reproducibility and inter-laboratory comparisons. (ii) Clinical validation: Verification that biomarker levels correlate with relevant health outcomes—for example, cholinesterase enzyme inhibition as an indicator of organophosphate neurotoxicity. (iii) Population validation: Evaluation of biomarker consistency across populations with varying genetic, environmental, and occupational backgrounds, which is especially important in developing countries. Comprehensive validation across these three levels enables biomarkers to serve as reliable evidence for occupational health surveillance, policymaking, and preventive interventions (Ougier et al., 2021; Meslin et al., 2022).

Practical Considerations for the Application of Biomarkers

Although biomarkers are powerful tools for occupational health surveillance, their application in practice requires careful consideration of multiple factors to ensure accurate results and to avoid misinterpretation. The following recommendations should be taken into account when implementing biomarker-based monitoring in the workplace:

1. Use of Combined Biomarkers

Relying on a single biomarker is often insufficient because some indicators may have high sensitivity but low specificity (e.g., trans, trans-muconic acid [t, t-MA] for benzene), whereas others exhibit high specificity but low sensitivity (e.g., S-phenylmercapturic acid [S-PMA]). Therefore, combining multiple biomarkers—such as S-PMA with t, t-MA, dialkyl phosphate metabolites (DAPs) with acetylcholinesterase (AChE)/butyrylcholinesterase (BChE), or 1-hydroxypyrene (1-OHP) with hydroxylated PAHs (OH-PAHs)—enhances accuracy and confidence in interpretation (Hernández et al., 2019).

2. Multi-Matrix Monitoring

In certain occupations, exposure occurs via multiple routes, including inhalation, dermal absorption, and ingestion. Collecting data from several matrices—such as air, skin, and urine—provides a more comprehensive exposure profile. This approach has proven particularly useful in professions with complex exposure pathways, such as firefighting and spray painting (WHO, 2021).

3. Early-Effect Biomarkers

Novel biomarkers such as kidney injury molecule-1 (KIM-1), neutrophil gelatinase-associated lipocalin (NGAL), micronuclei frequency, and DNA adducts can reveal early-stage organ or genetic damage before clinical symptoms appear. Employing these early-effect biomarkers supports proactive prevention and can reduce the long-term burden of occupational diseases (National Research Council, 1989).

4. Field Feasibility and Ethical Considerations

The practicality of biomarker use in occupational settings depends on factors such as sample accessibility, worker acceptability, cost, and laboratory capability. Noninvasive biological matrices such as urine or exhaled breath condensate should be prioritized to improve worker participation and minimize ethical barriers. Selection of methods should also align with each country's available resources and laboratory infrastructure (Organization for Economic Co-operation and Development, 2017).

5. Contextual Interpretation

Biomarker levels may be influenced by individual factors such as diet, smoking, medication, or lifestyle. Results should therefore be interpreted cautiously, considering these confounding variables. Biomarkers should not be used as a basis for employment decisions or discrimination but rather as preventive tools for improving occupational environments and worker safety (Cavallo et al., 2018).

6. Digital Health and Point-of-Care Technologies

Recent advances in biosensor-based point-of-care (POC) devices and digital health platforms have enabled near real-time biomonitoring in occupational settings. Wearable biosensors integrated with wireless communication systems have demonstrated considerable potential for continuous physiological and biochemical monitoring, enabling personalized exposure assessment and early detection of adverse health effects. These technologies facilitate real-time data collection and remote health surveillance, supporting the emerging paradigm of Precision Occupational Health. However, successful implementation requires rigorous calibration and

analytical validation against reference laboratory methods such as GC-MS or LC-MS/MS to ensure measurement accuracy, reproducibility, and reliability. Challenges remain regarding device standardization, data interoperability, cybersecurity, and infrastructure readiness, particularly in low- and middle-income countries. Despite these limitations, the integration of wearable sensors, cloud-based data management systems, and artificial intelligence may substantially enhance future occupational health surveillance and Precision Occupational Health programs (Zhang et al., 2024).

Biomarkers and Risk Assessment

Risk assessment is a fundamental process in managing occupational chemical hazards. It generally follows a four-step framework: (1) Hazard Identification, (2) Dose-Response Assessment, (3) Exposure Assessment, and (4) Risk Characterization (National Research Council, 1983; WHO, 2021b).

At each stage, biomarkers can significantly enhance the precision of evaluation—by providing direct evidence of exposure, biological effects, and individual susceptibility.

1. Hazard Identification

Hazard identification aims to determine whether a chemical substance can cause adverse health effects, drawing on toxicological, epidemiological, and mechanistic data. In this context, biomarkers of effect—such as the micronucleus assay, DNA adducts, or oxidative stress markers—play a crucial role in confirming biological damage in humans. For example, a study of hexavalent chromium (Cr(VI)) exposure demonstrated that workers with elevated chromium levels in blood and urine exhibited significantly higher micronucleus frequencies in respiratory epithelial cells, suggesting early carcinogenic mechanisms (Saber et al., 2025).

2. Dose-Response Assessment

This step analyzes the quantitative relationship between the dose of exposure and the biological response. Biomarkers of exposure provide critical data for this evaluation. For instance, urinary S-phenylmercapturic acid (S-PMA) levels have been correlated with decreased white blood cell counts among benzene-exposed workers (Lv et al., 2014). Such evidence not only demonstrates a measurable dose-response relationship but also supports the establishment of biological exposure indices (BEIs) used in occupational exposure control.

3. Exposure Assessment

Traditional exposure assessment typically relies on environmental measurements—such as airborne concentration—which may not capture inter-individual variability in absorption and metabolism. Biomarkers address this limitation by reflecting the internal dose more accurately. Examples include urinary dialkyl phosphate metabolites (DAPs) to assess exposure to organophosphate pesticides among children from an agricultural community (Hernández et al., 2019), and urinary 3-phenoxybenzoic acid (3-PBA) as a marker of pyrethroid exposure (Lehmle et al., 2022).

Noninvasive biological matrices—such as urine, saliva, and exhaled breath—offer practical and ethically acceptable alternatives for field applications, enhancing participation and the feasibility of population-level surveillance.

4. Risk Characterization

Risk characterization integrates all preceding data to estimate the likelihood and severity of potential adverse health effects. Biomarkers strengthen this stage by providing empirical evidence of subclinical or early-stage biological effects. For example, elevated levels of kidney injury molecule-1 (KIM-1) and neutrophil gelatinase-associated lipocalin (NGAL) have been observed in workers exposed to lead and cadmium, indicating

renal risk even when conventional kidney function parameters (e.g., creatinine clearance) remain normal (Jin et al., 2017). Recent evidence suggests that biomonitoring can strengthen risk characterization by integrating information on external exposure, internal dose, and biological responses. Biomarkers provide additional evidence for evaluating exposure–response relationships and may help reduce uncertainties associated with environmental monitoring alone. Furthermore, biomonitoring data can support the identification of potentially vulnerable worker populations and contribute to more informed occupational risk management and prevention strategies (Longo et al., 2021).

Health Effects of Occupational Chemical Exposure

Occupational exposure to chemical substances can affect multiple organ systems, with severity depending on the type of chemical, exposure dose, duration, and individual susceptibility. Evidence accumulated over the past decade has elucidated both toxicological mechanisms and health outcomes, many of which have been characterized through the use of biomarkers. The major affected systems are summarized below.

1. Hematopoietic System

Benzene is a prototypical hematotoxic and carcinogenic agent that affects bone marrow and blood cell formation. Chronic exposure is associated with hematological abnormalities and leukemia. Biomarkers such as S-phenylmercapturic acid (S-PMA) and trans, trans-muconic acid (t, t-MA) are widely used to assess benzene exposure and hematological parameters (Polyong & Thetkatuek, 2022b). Ling et al. (2024) Liang et al. demonstrated a significant association between urinary S-PMA concentrations and reduced leukocyte counts in workers exposed to benzene. The findings indicated that elevated S-PMA levels were linked to an increased risk of leukopenia, highlighting the value of S-PMA as a biologically relevant indicator of internal benzene dose and early hematotoxic effects in occupational settings.

2. Respiratory System

Workers in metal industries and welding operations are often exposed to hexavalent chromium (Cr(VI)) and nickel, both of which are linked to an increased risk of lung cancer. The SAM-Krom cohort (Saber et al., 2025) found that electroplating workers with elevated chromium levels in erythrocytes and urine exhibited higher frequencies of micronuclei in respiratory epithelial cells—evidence of DNA damage and early carcinogenic mechanisms. Similarly, spray painters and foam manufacturing workers exposed to isocyanates are at risk of developing occupational asthma, related to both inhalation and dermal absorption. Bello et al. (2020) reported that urinary hexamethylene diamine (HDA) levels correlated with environmental exposure and demonstrated that dermal contact was a major but underrecognized route of absorption. Integrating biomarker monitoring with pulmonary function testing provides a more accurate assessment of respiratory risk.

3. Nervous System

Organophosphate (OP) pesticides are classical neurotoxic agents that inhibit acetylcholinesterase (AChE) in erythrocytes and butyrylcholinesterase (BChE) in plasma. Decreased enzyme activity is associated with neurological symptoms such as headache, dizziness, and memory impairment. Zúñiga-Venegas et al. (2025) confirmed that urinary dialkyl phosphate metabolites (DAPs), combined with AChE/BChE measurements, correlated with neurobehavioral symptoms among Chilean farmers. In addition, exposure to organic solvents such as toluene and styrene has been linked to chronic neurobehavioral effects, including sleep disturbance and impaired concentration. Urinary metabolites such as hippuric acid (from toluene) have been applied as exposure biomarkers alongside neurological symptom questionnaires (Polyong & Thetkatuek, 2022a).

4. Hepatic and Renal Systems

The liver and kidneys are key target organs for heavy metals and organic solvents. Chronic exposure to lead and cadmium can impair renal function. Jin et al. (2017) reported that urinary Kidney Injury Molecule-1 (KIM-1) levels were elevated in lead-exposed workers, indicating its potential utility as an early biomarker of renal tubular injury before the onset of clinically apparent kidney dysfunction. For hepatic toxicity, exposure to organic solvents such as trichloroethylene (TCE) has been associated with elevated liver enzymes (ALT, AST, GGT) and oxidative stress biomarkers. In Thailand, Polyong and Thetkatuek (2024) found that gasoline station attendants with higher toluene exposure showed significantly increased liver enzyme levels, indicating hepatic stress.

5. Reproductive and Developmental Systems

Exposure to certain chemicals has been associated with reproductive and hormonal alterations. Male workers exposed to pyrethroid pesticides exhibited elevated urinary 3-phenoxybenzoic acid (3-PBA) levels, which correlated with disrupted sex hormone profiles and reduced sperm counts. A systematic review by Lehmler et al. (2022) confirmed this association across multiple populations, especially among agricultural workers. Similarly, exposure to cadmium and lead has been linked to menstrual disturbances, ovulatory dysfunction, and increased miscarriage risk, with biomarker levels of these metals showing correlations with reproductive hormone alterations and inflammatory markers.

6. Carcinogenic Effects

Several occupational chemicals are classified as Group 1 human carcinogens by the International Agency for Research on Cancer (IARC), including benzene, hexavalent chromium, nitrosamines, and asbestos. Relevant biomarkers of carcinogenesis include DNA adducts, micronuclei, and mutations in DNA repair genes, which can predict cancer risk before clinical symptoms manifest. Recent mechanistic studies on benzene toxicokinetics have demonstrated associations with hematologic and lymphoid malignancies (Polyong et al., 2024), underscoring the potential of biomarker-based approaches for early cancer risk prediction and preventive screening in occupational settings.

No single biomarker is universally applicable for all occupational chemical exposures. The suitability of a biomarker depends on its sensitivity, specificity, biological half-life, susceptibility to confounding factors, and feasibility of implementation in occupational health surveillance programs (Aylward et al., 2014; Viegas et al., 2020). Comparative evaluation is therefore essential for selecting appropriate monitoring strategies and interpreting biomonitoring results. Table 2 summarizes commonly used biomarkers for major occupational chemical groups, including their biological matrices, recommended sampling times, detection windows, potential confounding factors, and available biological guidance values.

Table 2 Comparative summary of common biomarkers for major occupational chemical exposures

Chemical Group	Biomarker	Matrix	Sampling Time	Detection Window	Confounders	Reference Value
Benzene	S-PMA	Urine	End of shift	24–48 h	Smoking	BEI
Benzene	t,t-MA	Urine	End of shift	24 h	Sorbic acid intake	BEI
Lead	Blood lead level	Blood	Any time	Weeks–months	Age, bone turnover	BEI

Table 2 (Cont.)

Chemical Group	Biomarker	Matrix	Sampling Time	Detection Window	Confounders	Reference Value
Cadmium	Urinary Cadmium	Urine	End of shift	Months–years	Smoking	HBM–GV
Organophosphate pesticides	DAPs	Urine	Post–shift	24–48 h	Diet	OBL
Isocyanates	Diamine metabolites	Urine	End of shift	24 h	Dermal exposure	Guidance value
PAHs	1–Hydroxypyrene	Urine	End of shift	24–48 h	Smoking, grilled food	BEI

Note: S–PMA, S–phenylmercapturic acid; t, t–MA, trans, trans–muconic acid; DAPs, dialkyl phosphate metabolites; PAHs, polycyclic aromatic hydrocarbons; BEI, Biological Exposure Index; OBL, Occupational Biomonitoring Level; HBM–GV, Human Biomonitoring Guidance Value.

Emerging Technologies for Future Biomarker Development

Continuous advancements in analytical and biomedical technologies have been instrumental in overcoming key limitations of conventional biomarker applications such as low sensitivity, limited specificity, and susceptibility to confounding factors. Recent research trends have introduced several high–potential approaches that promise to revolutionize biomonitoring and occupational health surveillance.

1. Omics–Based Biomarkers

The integration of genomics, transcriptomics, proteomics, and metabolomics has enabled the discovery of novel biomarkers reflecting molecular–level alterations caused by chemical exposures. For instance, microRNA profiles have been associated with heavy metal exposure, and metabolomic signatures have been linked to oxidative stress from polycyclic aromatic hydrocarbons (PAHs), offering high specificity and early detection before clinical manifestation (Brandt–Rauf et al., 2002). In Thailand, recent proteomic research among gasoline station attendants (B–GSA) revealed four serum proteins: HBS1–like protein, non–structural maintenance of chromosomes element 1 homolog, proprotein convertase subtilisin/kexin type 4, and zinc finger protein 658 that were significantly elevated compared to a control group. These proteins were associated with apoptosis, cancer–related pathways, p53 signaling, and TNF signaling, suggesting their potential as molecular biomarkers for benzene–induced toxicity (Polyong et al., 2024).

2. Non–Invasive Biomarkers

To improve worker acceptance and sample collection feasibility, non–invasive biomarker approaches have gained attention. Examples include exhaled breath condensate (EBC) for detecting hexavalent chromium (Leese et al., 2023) and salivary biomarkers for assessing pesticide or solvent exposure (Wren et al., 2024). These matrices provide a convenient and ethically acceptable means of biological monitoring, particularly for field studies and large–scale population screening.

3. Multi–Matrix Monitoring

Multi–matrix monitoring combines biological and environmental samples, such as urine, skin wipes, and workplace air, to provide a more comprehensive assessment of occupational exposure. This integrated approach is particularly useful in complex occupational settings where workers may be exposed through multiple routes (Viegas et al., 2020).

4. Digital Health and Point-of-Care Testing

Innovations in biosensors and real-time portable devices are transforming biomonitoring into a field-deployable activity. Portable devices that can detect oxidative stress markers in urine or pesticide residues in saliva enable real-time surveillance at workplaces. These point-of-care (POC) tools can significantly enhance early detection and timely interventions in occupational settings (Apel et al., 2020).

5. Precision Occupational Health

The future direction of occupational health is moving toward Precision Occupational Health, an extension of precision medicine that integrates biomarker data with genetic, behavioral, and environmental information to design individualized prevention strategies. For example, combining CYP450 genotyping with benzene exposure biomarkers may help identify genetically susceptible workers who require enhanced protective measures (Lewoń-Mrozek et al., 2024).

As shown in Table 3, traditional biomarkers remain the most practical approach for routine occupational health surveillance because of their relatively low cost and established validation. In contrast, omics-based biomarkers offer greater sensitivity for detecting early molecular changes but require advanced analytical infrastructure and specialized expertise. Digital health technologies provide opportunities for real-time monitoring and rapid intervention; however, challenges related to standardization, validation, and data management remain important considerations for widespread implementation.

Table 3 Comparison of traditional biomarkers, omics-based biomarkers, and digital health approaches in occupational health surveillance

Aspect	Traditional Biomarkers	Omics-Based Biomarkers	Digital Health Approaches
Primary Purpose	Exposure and effect monitoring	Molecular pathway identification and early biological changes	Real-time exposure and health monitoring
Sensitivity	Moderate	High	Moderate-High
Specificity	Moderate-High	High	Variable
Detection Stage	Established exposure or effect	Preclinical molecular alterations	Immediate or near real-time monitoring
Laboratory Requirement	Standard laboratory	Advanced laboratory and bioinformatics support	Portable devices and digital platforms
Technical Expertise	Moderate	High	Moderate
Cost	Low-Moderate	High	Moderate-High
Feasibility for Routine Surveillance	High	Limited	Emerging
Real-Time Monitoring	No	No	Yes
Suitability in Resource-Limited Settings	High	Low	Moderate

Sources: Adapted from Viegas et al. (2020), Longo et al. (2021), Capone et al. (2024), and Zhang et al. (2024).

Ethical and Legal Considerations in Biomonitoring and Genetic Data

Biomonitoring programs should be implemented with informed consent, ensuring that workers understand the purpose of testing, the nature of the collected data, and the potential implications of the results. Protection of

privacy, confidentiality, and personal data is essential, particularly when genetic or molecular information is collected, as unauthorized disclosure may result in stigma, discrimination, or adverse employment consequences. Clear and transparent communication of biomonitoring results should be understandably provided to workers, together with appropriate occupational health guidance and follow-up actions. Furthermore, biomonitoring and genetic information should not be used to unfairly restrict employment opportunities, influence hiring decisions, or discriminate against workers based on biological susceptibility or genetic characteristics. These considerations are particularly important as Precision Occupational Health and omics-based approaches become increasingly integrated into workplace health surveillance systems. International guidance emphasizes that biomonitoring programs should primarily support worker protection, disease prevention, and risk reduction while respecting ethical principles, human rights, data protection requirements, and applicable legal frameworks (Viegas et al., 2020). Therefore, responsible governance, transparency, and stakeholder engagement are essential to ensure the ethical implementation of biomonitoring and genetic data in occupational health practice.

Comparison of traditional biomarkers, omics-based biomarkers, and digital health approaches reveals important differences in practical application. Traditional biomarkers are generally well validated, relatively inexpensive, and suitable for routine occupational health surveillance; however, they may have limited sensitivity for detecting early biological changes. Omics-based biomarkers offer greater sensitivity and the ability to identify molecular alterations before clinical manifestations occur, but they require advanced laboratory infrastructure, specialized expertise, and substantially higher costs. Digital health technologies, including wearable biosensors and point-of-care devices, provide opportunities for real-time monitoring and rapid decision-making, although challenges related to validation, standardization, and data management remain. Therefore, the selection of biomonitoring approaches should consider the intended purpose, available resources, analytical requirements, and feasibility of implementation in occupational settings.

Conclusion and Suggestions

Biomarkers play a crucial role in bridging environmental and occupational exposure with measurable health outcomes. The growing body of evidence underscores their importance in improving the precision of chemical risk assessment, facilitating early detection of organ-specific toxicity, and identifying vulnerable populations. However, current applications are limited by variability in specificity, analytical complexity, and accessibility in low-resource settings. Future directions emphasize integration of omics-based technologies, non-invasive sampling, and multi-matrix monitoring to enhance sensitivity and real-time applicability. Advances in digital health and point-of-care testing will transform biomonitoring into a proactive, field-deployable tool for occupational surveillance. The emerging concept of Precision Occupational Health—which combines biomarkers with genetic, behavioral, and environmental data—marks a paradigm shift toward individualized prevention and policy formulation. In this context, biomarkers are not merely diagnostic tools but essential instruments for achieving equitable and sustainable protection of workers' health in the evolving industrial landscape.

The findings of this review may also support the development of occupational health policies, biological monitoring guidelines, and evidence-based regulatory frameworks at national and international levels. Government agencies, occupational health authorities, labor protection organizations, and industry stakeholders may utilize validated biomarker information to strengthen occupational health surveillance systems, improve

exposure control programs, establish biological guidance values, and prioritize preventive interventions for high-risk worker populations. Wider implementation of biomonitoring strategies may contribute to more effective occupational disease prevention, enhanced regulatory decision-making, and sustainable protection of workers' health in rapidly evolving industrial environments.

Suggestions: This review highlights the need to integrate validated biomarkers into occupational health surveillance beyond conventional environmental monitoring. The combined application of biomarkers of exposure, effect, and susceptibility is recommended to improve the assessment of internal dose, early biological effects, and individual variability. Biomarker selection should emphasize clear dose-response relationships and standardized analytical quality. The incorporation of early-effect biomarkers can facilitate timely intervention before clinical disease onset. Non-invasive sampling and point-of-care technologies should be promoted to enhance feasibility in field and resource-limited settings. Future research should advance omics-based and digital health approaches to support Precision Occupational Health. Biomarker data must be interpreted ethically and used as preventive tools to inform risk management and policy development, rather than for discriminatory purposes. Future collaborative efforts among researchers, occupational health practitioners, policymakers, and regulatory agencies are essential to facilitate the translation of biomarker research into workplace health protection programs and national occupational health policies.

Author Contributions

Chan Pattama Polyong: Conceptualization; Methodology; Literature search and selection; Formal analysis and synthesis; Writing original draft; Writing-Review & Editing; Project administration.

Thawatchai Eksanti: Methodology; Formal analysis and synthesis; Writing-Review & Editing.

Pichitra Patipat: Literature search and selection; Data curation; Writing-Review & Editing.

Kornwika Harasarn: Literature search and selection; Data curation; Writing-Review & Editing.

All authors have read and agreed to the published version of the manuscript.

Conflict of Interests

All authors declare that they have no conflicts of interest.

Funding

The authors received no financial support for the review of this article.

Declaration of Generative AI and AI-assisted Technologies

During the preparation of this manuscript, the authors used ChatGPT (GPT-5.6 Thinking; OpenAI, San Francisco, CA, USA) for English language checking and editorial refinement, as well as digital design tools for supporting the development of the abstract graphic. These tools were used solely to improve clarity and presentation, and all scientific content, interpretation, and conclusions are the responsibility of the authors.

References

- Angerer, J., Ewers, U., & Wilhelm, M. (2018). Human biomonitoring: State of the art. *International Journal of Hygiene and Environmental Health*, 211(3–4), 201–228. <http://doi.org/10.1016/j.ijheh.2007.01.024>
- Apel, P., Rousselle, C., Lange, R., Sissoko, F., Kolossa-Gehring, M., & Ougier, E. (2020). Human biomonitoring initiative (HBM4EU) – strategy to derive human biomonitoring guidance values (HBM-GVs) for health risk assessment. *International Journal of Hygiene and Environmental Health*, 230, 113622. <http://doi.org/10.1016/j.ijheh.2020.113622>
- Aylward, L. L., Hays, S. M., Smolders, R., Koch, H. M., Cocker, J., Jones, K., Warren, N., Levy, L., & Bevan, R. (2014). Sources of variability in biomarker concentrations, *Journal of Toxicology and Environmental Health, Part B: Critical Reviews*, 17(1), 45–61. <https://doi.org/10.1080/10937404.2013.864250>
- Barr, D. B., Bravo, R., Weerasekera, G., Calabiano, L. M., Whitehead, R. D., Olsson, A. O., & Needham, L. L. (2004). Concentrations of dialkyl phosphate metabolites of organophosphorus pesticides in the U.S. population. *Environmental Health Perspectives*, 112(2), 186–200. <http://doi.org/10.1289/ehp.6503>
- Bolt, H. M., & Thier, R. (2006). Relevance of the deletion polymorphisms of the glutathione S-transferases GSTT1 and GSTM1 in pharmacology and toxicology. *Current Drug Metabolism*, 7(6), 613–628. <http://doi.org/10.2174/138920006778017786>
- Bonassi, S., El-Zein, R., Bolognesi, C., & Fenech, M. (2011). Micronuclei frequency in peripheral blood lymphocytes and cancer risk: Evidence from human studies. *Mutagenesis*, 26(1), 93–100. <http://doi.org/10.1093/mutage/geq075>
- Brandt-Rauf, P. W., Luo, J. C., Cheng, T. J., Du, C. L., Wang, J. D., Rosal, R., & Marion, M. J. (2002). Molecular biomarkers and epidemiologic risk assessment. *Human and Ecological Risk Assessment*, 8(6), 1295–1301. <https://doi.org/10.1080/20028091057367>
- Capone, P., Chiarella, P., & Sisto, R. (2024). Advanced technologies in genomic toxicology: Current trend and future directions. *Current Opinion in Toxicology*, 37, 100444. <https://doi.org/10.1016/j.cotox.2023.100444>
- Cavallo, D., Tranfo, G., Ursini, C. L., Freseghna, A. M., Ciervo, A., Maiello, R., & Iavicoli, S. (2018). Biomarkers of early genotoxicity and oxidative stress for occupational risk assessment of exposure to styrene in the fibreglass reinforced plastic industry. *Toxicology Letters*, 298, 53–59. <http://doi.org/10.1016/j.toxlet.2018.06.006>
- Costa, L. G., Giordano, G., Cole, T. B., Marsillach, J., & Furlong, C. E. (2013). Paraoxonase 1 (PON1) as a genetic determinant of susceptibility to organophosphate toxicity. *Toxicology*, 307, 115–22. <http://doi.org/10.1016/j.tox.2012.07.011>
- Cui, S., Pang, B., Yan, H., Wu, B., Li, M., Xing, C., & Li, J. (2022). Using urinary biomarkers to estimate benzene exposure. *Toxics*, 10(11), 636. <http://doi.org/10.3390/toxics10110636>
- Dalmolin, S. P., Dreon, D. B., Thiesen, F. V., & Dallegrave, E. (2020). Biomarkers of occupational exposure to pesticides: Systematic review of insecticides. *Environmental Toxicology and Pharmacology*, 75, 103304. <http://doi.org/10.1016/j.etap.2019.103304>

- Furlong, C. E., Holland, N. T., Richter, R. J., Bradman, A., & Eskenazi, B. (2006). PON1 status of farmworker mothers and children as a predictor of organophosphate sensitivity. *Pharmacogenetics and Genomics*, 16(3), 183–190. <http://doi.org/10.1097/01.fpc.0000189796.21770.d3>
- García-Closas, M., Malats, N., Silverman, D., Dosemeci, M., Kogevinas, M., & Hein, D. W. (2005). NAT2 slow acetylation, GSTM1 null genotype, and risk of bladder cancer: Results from the Spanish bladder cancer study and meta-analyses. *The Lancet*, 366(9486), 649–659. [http://doi.org/10.1016/S0140-6736\(05\)67137-1](http://doi.org/10.1016/S0140-6736(05)67137-1)
- Murray, C. J., Aravkin, A. Y., Zheng, P., Abbafati, C., Abbas, K. M., Abbasi-Kangevari, M., ... & Borzouei, S. (2020). Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *The Lancet*, 396(10258), 1223–1249. [http://doi.org/10.1016/S0140-6736\(20\)30752-2](http://doi.org/10.1016/S0140-6736(20)30752-2)
- Hernández, A. F., Lozano-Paniagua, D., González-Alzaga, B., Kavvalakis, M. P., Tzatzarakis, M. N., López-Flores, I., Aguilar-Garduño, C., Caparros-Gonzalez, R. A., Tsatsakis, A. M., & Lacasaña, M. (2019). Biomonitoring of common organophosphate metabolites in hair and urine of children from an agricultural community. *Environment International*, 131, 105003. <https://doi.org/10.1016/j.envint.2019.104997>
- Hughes, D., Thongkum, W., Tudpor, K., Turnbull, N., Yukalang, N., Sychareun, V., Van Vo, T., Win, L. L., Watkins, A., & Jordan, S. (2021). Pesticide use and health impacts on farmers in Thailand, Vietnam, and Lao PDR: Protocol for a survey of knowledge, behaviours and blood acetyl cholinesterase concentrations. *PLoS One*, 16(9), e0258134. <http://doi.org/10.1371/journal.pone.0258134>
- International Labour Organization. (2021). *Exposure to hazardous chemicals at work and resulting health impacts: A global review*. International Labour Office. <https://www.ilo.org/publications/exposure-hazardous-chemicals-work-and-resulting-health-impacts-global>
- Jin, Y., Shao, X., Sun, B., Miao, C., Li, Z., & Shi, Y. (2017). Urinary kidney injury molecule-1 as an early diagnostic biomarker of obstructive acute kidney injury and development of a rapid detection method. *Molecular Medicine Reports*, 15(3), 1229–1235. <http://doi.org/10.3892/mmr.2017.6103>
- Lanphear, B. P., Rauch, S., Auinger, P., Allen, R. W., & Hornung, R. W. (2018). Low-level lead exposure and mortality in US adults: A population-based cohort study. *The Lancet Public Health*, 3(4), e177–e184. [http://doi.org/10.1016/S2468-2667\(18\)30025-2](http://doi.org/10.1016/S2468-2667(18)30025-2)
- Leese, E., Jones, K., Bocca, B., Bousoumah, R., Castano, A., Galea, K. S., & van Dael, M. (2023). HBM4EU chromates study—the measurement of hexavalent and trivalent chromium in exhaled breath condensate samples from occupationally exposed workers across Europe. *Toxicology Letters*, 375, 59–68. <https://doi.org/10.1016/j.toxlet.2022.12.009>
- Lehmle, H. J., Simonsen, D., Garcia, A. Q., Irfan, N. M., Dean, L., Wang, H., Elsterman, M., Li, X. (2022). A systematic review of human biomonitoring studies of 3-phenoxybenzoic acid, a urinary biomarker of pyrethroid insecticide exposure, 1997 to 2019. *Hygiene and Environmental Health Advances*, 4, 100018. <http://doi.org/10.1016/j.heha.2022.100018>
- Lewoń-Mrozek, D., Kurzynoga, J., Jędrzejewski, P., Kędzierska, K., Partyka, A., Kuriata-Kordek, M., & Ściskalska, M. (2024). Molecular structure of paraoxonase-1 and its modifications in relation to enzyme

- activity and biological functions: A comprehensive review. *International Journal of Molecular Sciences*, 25(23), 13129. <http://doi.org/10.3390/ijms252313129>
- Liang, B., Zhong, Y., Chen, K., Zeng, L., Li, G., & Zheng, J. (2018). Serum plasminogen as a potential biomarker for the effects of low-dose benzene exposure. *Toxicology*, 410, 59–64. <https://doi.org/10.1016/j.tox.2018.09.004>
- Longo, V., Brunetti, G., Anzivino, E., D'Errico, M. N., & De Maria, L. (2021). Biomonitoring and health risk assessment in occupational exposure to chemicals: Current status and future perspectives. *International Journal of Environmental Research and Public Health*, 18(19), 10236. <https://doi.org/10.3390/ijerph181910236>
- Lv, B. H., Song, S. Z., Zhang, Z., Mei, Y., & Ye, F. L. (2014). Urinary S-phenylmercapturic acid as a key biomarker for measuring occupational exposure to low concentrations of benzene in Chinese workers: a pilot study. *Journal of Occupational and Environmental Medicine*, 56(3), 319–325. <https://doi.org/10.1097/JOM.0000000000000098>
- Meslin, M., Beausoleil, C., Zeman, F.A., Antignac, J. P., Kolossa-Gehring, M., Rousselle, C., & Apel, P. (2022). Human biomonitoring guidance values (HBM-GVs) for bisphenol S and assessment of the risk due to exposure to bisphenols A and S, in Europe. *Toxics*, 10(5), 228. <http://doi.org/10.3390/toxics10050228>
- National Research Council. (1983). *Risk assessment in the federal government: Managing the process*. National Academies Press. <https://pubmed.ncbi.nlm.nih.gov/25032414/>
- National Research Council. (1989). *Biological markers in reproductive toxicology*. National Academies Press. <https://pubmed.ncbi.nlm.nih.gov/25032456/>
- Organization for Economic Co-operation and Development. (2017). *Guidance document on good in vitro method practices (GIVIMP)*. OECD Publishing. https://www.oecd.org/en/publications/guidance-document-on-good-in-vitro-method-practices-givimp_9789264304796-en.html
- Ougier, E., Zeman, F., Antignac, J. P., Rousselle, C., Lange, R., Kolossa-Gehring, M., & Apel, P. (2021). Human biomonitoring initiative (HBM4 EU): Human biomonitoring guidance values (HBM-GVs) derived for bisphenol A. *Environment International*, 154, 106563. <http://doi.org/10.1016/j.envint.2021.106563>
- Polyong, C. P., Roytrakul, S., Sirivarasai, J., Yingratanasuk, T., & Thetkathuek, A. (2024). Novel serum proteomes expressed from benzene exposure among gasoline station attendants. *Biomarkers Insights*, 19, <http://doi.org/10.1177/11772719241259604>
- Polyong, C. P., & Thetkathuek, A. (2022a). Factors affecting the prevalence of neurological symptoms among workers at gasoline stations in Rayong Province, Thailand. *Environmental Analysis, Health and Toxicology*, 37(2), e2022009. <http://doi.org/10.5620/eaht.2022009>
- Polyong, C. P., & Thetkathuek, A. (2022b). Factors influencing hematological parameters among laborers at a gas service station in Rayong Province, Thailand. *Journal of Public Health and Development*, 20(3), 47–53. <http://doi.org/10.55131/jphd/2022/200304>
- Polyong, C. P., & Thetkathuek, A. (2024). Liver, kidney, glycohemoglobin, neurotransmitters, heart markers, and factors affecting blood biochemicals among workers at gas service stations, Thailand. *Journal of Public Health and Emergency*, 8(3), 1–13. <http://doi.org/10.21037/jphe-24-26>

- Rahimpoor, R., Jalilian, H., Mohammadi, H., & Rahmani, A. (2023). Biological exposure indices of occupational exposure to benzene: A systematic review. *Heliyon*, 9(11), e21576. <https://doi.org/10.1016/j.heliyon.2023.e21576>
- Saber, A. T., Levin, M., Kines, P., Aimonen, K., Givélet, L., Andersen, C., Huusom, A. J., Carøe, T., Ebbenhøj, N. E., Christensen, F. M., Jiang, Z., Lundh, T., Tinnerberg, H., Albin, M., Engfeldt, M., Broberg, K., Catalan, J., Loeschner, K., Fuglsang, K., & Vogel, U. (2025). The SAM-Krom biomonitoring study shows occupational exposure to hexavalent chromium and increased genotoxicity in Denmark. *International Journal of Hygiene and Environmental Health*, 264, 114444. <http://doi.org/10.1016/j.ijheh.2024.114444>
- Sapbamrer, R., & Hongsibsong, S. (2014). Organophosphorus pesticide residues in vegetables from farms, markets, and a supermarket around Kwan Phayao Lake of Northern Thailand. *Archives of Environmental Contamination and Toxicology*, 67(1), 60–67. <http://doi.org/10.1007/s00244-014-0014-x>
- Sexton, K., Needham, L., & Pirkle, J. (2004). Human biomonitoring of environmental chemicals: Measuring chemicals in human tissues is the “gold standard” for assessing people’s exposure to pollution. *Journal of American Science*, 92(1), 38–45.
- Umicevic, N., Kotur-Stevuljevic, J., Paleksic, V., Djukic-Cosic, D., Miljakovic, E. A., Djordjevic, A. B., & Antonijevic, B. (2022). Liver function alterations among workers in the shoe industry due to combined low-level exposure to organic solvents. *Drug and Chemical Toxicology*, 45(4), 1907–1914. <https://doi.org/10.1080/01480545.2021.1894703>
- Viegas, S., Jeddi, Z. M., Hopf, B. N., Bessems, J., Palmen, N., Galea, S. K., Jones, K., Kujath, P., Duca, R. C., Verhagen, H., Santonen, T., & Pasanen-Kase, R. (2020). Biomonitoring as an underused exposure assessment tool in the occupational safety and health context: challenges and way forward. *The International Journal of Environmental Research and Public Health*, 17(16), 5884. <http://doi.org/10.3390/ijerph17165884>
- World Health Organization. (2017). *Biological monitoring of chemical exposure in the workplace: Guidelines*. World Health Organization. <https://iris.who.int/server/api/core/bitstreams/4512ca7d-2c78-44ad-a2f8-f89ad34d3540/content>
- World Health Organization. (2021a). *Preventing disease through healthy environments: Exposure to chemicals*. World Health Organization. <https://iris.who.int/server/api/core/bitstreams/eb8328cb-022a-4daa-81ec-1b5a071035d5/content>
- World Health Organization. (2021b). *WHO human health risk assessment toolkit: Chemical hazards*. World Health Organization. <https://www.who.int/publications/i/item/9789240035720>
- Wren, M., Robson, M., & Buckley, B. (2024). A novel biomonitoring method to detect pyrethroid metabolites in saliva of occupationally exposed workers as a tool for risk assessment. *Human and Ecological Risk Assessment: An International Journal*, 30(3–4), 269–288. <https://doi.org/10.1080/10807039.2024.2329625>
- Zhang, J., Guo, Y., Lin, Y. R., Ma, B. C., Ge, X. R., Zhang, W. Q., Zhang, N. X., Yang, S. M., & Hui, C. Y. (2024). Detection of cadmium in human biospecimens by a cadmium-selective whole-cell biosensor based on deoxyviolacein. *ACS Biomaterials Science & Engineering*, 10(6), 4046–4058. <https://doi.org/10.1021/acsbiomaterials.3c01814>