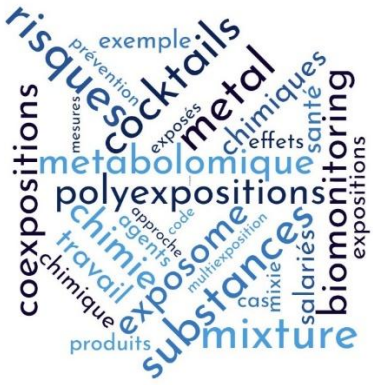


Bulletin de veille
Polyexpositions chimiques
N°17 – octobre, novembre 2026

Objectif : la polyexposition homogène chimie/chimie est un sujet de plus en plus préconisé pour étudier l'évaluation du risque professionnel et sa prévention. L'objectif est de connaitre les travaux récents qui sont publiés sur le sujet et identifier des moyens d'analyse, et d'interprétation de cette co-exposition à plusieurs composés chimiques.

Ce bulletin a été réalisé à partir d'une surveillance de littérature récente sur les bases Web of Sciences et la base documentaire INRS-Biblio.

La validation des informations fournies (exactitude, fiabilité, pertinence par rapport aux principes de prévention, etc.) est du ressort des auteurs des articles signalés dans la veille. Les informations ne sont pas le reflet de la position de l'INRS. Les éléments issus de cette veille sont fournis sans garantie d'exhaustivité.

Les liens mentionnés dans le bulletin donnent accès aux documents sous réserve d'un abonnement à la ressource.

Actualités web

- 28 septembre 2026. Pandey N. Healthandme.com
  485 'Inactive' Chemicals In US Pesticide Products Linked To Breast Cancer.
  https://www.healthandme.com/health-news/485-inactive-chemicals-in-us-pesticide-products-linked-to-breast-cancer-article-156238067
  Lire l'article

- 8 octobre 2026. Auteure : Carmona M. Inforisques.fr/actualites
  Titre : **Bruit, solvants, FDS : comment repérer les postes où le risque auditif est sous-évalué ?**
  Lire l'article

- **Mise à jour des règles de protection des travailleurs contre l'exposition à des produits chimiques dangereux.** Source : Parlement européen. Date : 6 octobre 2026
  https://www.europarl.europa.eu/pdfs/news/expert/2026/10/press_release/20261002IPR47899/20261002IPR47899_fr.pdf

- **L'UE renforce la protection des travailleurs exposés à des substances dangereuses**
  Source : Vie-publique.fr. Date : 9 octobre 2026
  https://www.vie-publique.fr/en-bref/304887-lue-renforce-la-protection-des-travailleurs-aux-substances-dangereuses

- **Epidémie de cancer, mieux reconnaitre les expositions professionnelles multiples**
  Hunsmann M., Marchand A., Wolf J., « Épidémie de cancer : mieux reconnaître les expositions professionnelles », Impacts. CNRS Sciences humaines & sociales, n°2, 2026.
  En savoir plus.
  https://www.cnrs.fr/sites/default/files/press_info/2026-09/PB2_VF.pdf

Table

1. INRS-Biblio. Expositions combinées 3
2. Biomonitoring des mélanges chimiques 4
3. Approches métabolomiques 8
4. Modèles, outils de mesures 9
5. Polyexpositions aux métaux lourds 9
   - 5.1 Effets neurologiques et santé mentale 9
   - 5.2 Effets rénaux – Néphrotoxicité 10
   - 5.3 Effets inflammatoires et stress oxydatif 12
   - 5.4 Effets génotoxiques et cancérogènes 14
   - 5.5. Vieillissement biologique 15
6. Multiples expositions aux polluants ambiants, VOCs, pesticides 16

1. INRS-Biblio. Expositions combinées

Tartaglia M, Jaunas K, Audignon-Durand S, et al.

Multiple maternal occupational exposures during pregnancy and newborn size at birth : analysis of the ELFE cohort, a French longitudinal study of children. (Expositions professionnelles multiples des femmes pendant la grossesse et taille des nouveaux-nés à la naissance : analyse de la cohorte ELFE, une étude longitudinale française sur les enfants).

Scandinavian Journal of Work Environment and Health, vol. 52, n° 5, septembre 2026, pp. 514-527, ill., bibliogr. (En anglais)

Cette étude épidémiologique examine les associations entre les expositions professionnelles multiples des femmes enceintes et la croissance fœtale, à partir des données de la cohorte française ELFE. L'analyse porte sur 12 851 couples mère-enfant et s'intéresse à trois indicateurs : le risque de naissance d'un enfant petit pour l'âge gestationnel, le poids de naissance et le périmètre crânien.

Parmi les 47 facteurs professionnels initialement évalués, les auteurs ont sélectionné les expositions chimiques, physiques, biomécaniques, organisationnelles et psychosociales susceptibles d'influencer la croissance intra-utérine, sur la base des connaissances et de la littérature scientifiques existantes. Les expositions ont été estimées à l'aide de matrices emplois-expositions et analysées au moyen de modèles de régression ajustés sur plusieurs facteurs de confusion, en tenant compte du trimestre de grossesse durant lequel les femmes ont cessé de travailler.

Les résultats montrent que l'exposition professionnelle aux particules ultrafines est associée à une augmentation du risque de naissance d'un enfant petit pour l'âge gestationnel et à une diminution du poids de naissance. L'exposition aux solvants oxygénés est associée à une réduction du périmètre crânien et à un risque accru de retard de croissance chez les femmes ayant travaillé jusqu'au troisième trimestre. Une forte contrainte psychosociale augmente également ce risque chez celles ayant arrêté leur activité au premier ou au deuxième trimestre.

Ces résultats suggèrent l'influence possible de facteurs chimiques et intenses à l'œuvre sur la croissance fœtale, en particulier selon le trimestre au cours duquel les femmes enceintes ont cessé de travailler. Les auteurs soulignent les limites liées à l'estimation des expositions multiples et à la possibilité d'interactions non identifiées et demandent des études supplémentaires pour explorer les mécanismes biologiques sous-jacents.

Référence INRS-Biblio : 774389

Lien vers l'article : https://doi.org/10.5271/sjweh.4289

****

HAGEMAN G. ; VAN BROEKHUIZEN P. ; NIHOM J.

Health conditions in aircrew. Association with neurotoxic substances and other occupational factors. (Troubles de santé chez le personnel navigant. Associations avec des substances neurotoxiques et d'autres facteurs professionnels).

Journal of Occupational and Environmental Hygiene, vol. 23, n° 3, mars 2026, pp. 191–207, ill., bibliogr. (En anglais)

Cette revue examine les troubles de santé du personnel navigant en relation avec les contaminants de l'air des cabines et d'autres facteurs professionnels. Une recherche bibliographique portant sur les publications disponibles jusqu'en mai 2025 a conduit à sélectionner 162 articles parmi 672 références examinées. Les travaux concernaient la neurotoxicité ou l'immunotoxicité de l'air contaminé des cabines, les cancers chez le personnel navigant et les facteurs professionnels susceptibles d'y contribuer. Les auteurs rapportent notamment une association entre l'exposition aux organophosphorés et certains auto-anticorps neuronaux accompagnés de symptômes neurologiques. Les produits issus de la dégradation de l'ozone pourraient également présenter des propriétés neurotoxiques et cancérogènes. La perturbation des rythmes circadiens liée au travail de nuit influence notamment le système immunitaire, le métabolisme de substances toxiques et certaines hormones.

Les rayonnements cosmiques sont également examinés comme facteur professionnel. Les auteurs considèrent que l'exposition combinée à plusieurs substances et facteurs professionnels pourrait contribuer aux symptômes décrits chez le personnel navigant et à certains risques de cancer.

Référence INRS-Biblio : 773354

Lien vers l'article : https://doi.org/10.1080/15459624.2025.2582821

****

JOHNSON Z. ; SLAGLEY J. ; SCHAAL N. ; MATTIE D. ; ET COLL.

Retrospective cohort study of pure tone audiometry hearing changes from ototoxic metals and solvents, continuous noise, and impulse noise exposures at Hill Air Force Base from 2005 to 2019. (Etude de cohorte rétrospective des modifications de l'audition évaluées par audiométrie tonale en lien avec l'exposition à des métaux et solvants ototoxiques, au bruit continu et au bruit impulsionnel à la base aérienne de Hill, de 2005 à 2019).

Journal of Occupational and Environmental Hygiene, vol. 23, n° 2, février 2026, pp. 100-112, ill., bibliogr. (En anglais)

Cette étude rétrospective évalue le risque de perte auditive lié à l'exposition professionnelle combinée à des métaux et solvants ototoxiques, au bruit continu et au bruit impulsionnel chez 893 travailleurs d'une base aérienne américaine suivis entre 2005 et 2019. Les données d'exposition et de surveillance audiométrique ont été analysées selon différents groupes d'exposition. Les travailleurs exposés à des substances ototoxiques présentent globalement un risque de perte auditive supérieur à ceux exposés uniquement au bruit, sans différence statistiquement significative dans cette population. L'analyse combinée avec les données d'une autre base aérienne met toutefois en évidence des augmentations significatives du risque pour certaines expositions. Le risque le plus élevé est observé lors de l'exposition simultanée aux métaux, aux solvants et au bruit continu. L'âge et la durée du suivi audiométrique sont également associés à la perte auditive.

Référence INRS-Biblio : 773335

Lien vers l'article : https://doi.org/10.1080/15459624.2025.2569365

****

2. Biomonitoring des mélanges chimiques

Crepet, A., Mckeon, H., Angeli, K., Bil, W., Cox, B., Govarts, E.*, et al.*
Strategy for mixture risk assessment using European human biomonitoring data : lessons learned from applications to pesticides, per- and polyfluoroalkyl substances and metal(loid)s.
Environ Int, 2026, Vol. 217, article 110560.

Humans are exposed daily to mixtures of chemicals from multiple sources and routes, including diet and the environment. These combined exposures may cause adverse health effects that are not adequately captured by conventional substance-by-substance risk assessment, due to the inherent complexity of assessing combined risks. To address this gap, the Partnership for the Assessment of Risks from Chemicals (PARC) Real-life Mixtures project aims to consolidate scientific knowledge regarding mixture risk assessment (MRA). In synergy with ongoing activities of European agencies and other initiatives, this project developed a strategy to perform MRA using human biomonitoring (HBM) data.
The approach consists of five steps: (1) prioritisation of chemical mixtures of interest for human health to guide case-study selection; (2) collection and organisation of the data required for MRA, including exposure, hazard, and toxicokinetic information; (3) development of methods for conducting MRA using HBM data; (4) implementation of these methods within the Monte Carlo Risk Assessment (MCRA) toolbox; and (5) application of the strategy to prioritised case studies.

Three chemical families and four associated adverse health outcomes were selected based on the results of PARC priority process: pesticides affecting the nervous system, per- and polyfluoroalkyl substances (PFAS) affecting the immune system, and metal(loid)s affecting kidney function and neurodevelopment. HBM data from studies conducted across Europe and Greenland were harmonised using the HBM data toolkit. Hazard and toxicokinetic data were compiled to derive internal toxicological values suitable for MRA. The MRA was then performed in a harmonised way for each case study using the MCRA toolbox.
The strategy developed within the PARC Real-life Mixtures project provides a proof-of-concept for conducting HBM-based MRA and for informing policymakers. Future research will focus on reducing uncertainties and expanding the approach to additional chemicals with common health endpoints and co-exposure.
https://doi.org/10.1016/j.envint.2026.110560

****

Braeuer, S., Feuerstein, M. L., Buerki-Thurnherr, T., Warth, B., Koellensperger, G.
An integrated workflow for combined organic and inorganic chemical exposome analysis.
Talanta, 2027, vol. 312 Part B, article : 130499.

Humans are exposed to a multitude of non-genetic factors throughout their lives, all of which are encompassed in the concept of the exposome. To assess its chemical component, combinations of complementary analytical techniques are needed for broad chemical space coverage. However, approaches for combined organic and inorganic analysis remain scarce and are further constrained by limited sample availability (e.g., in historical biobanks or preterm infants), as individual techniques require different sample preparation workflows.
Therefore, we developed and evaluated an approach to combine sample preparation and analysis of organic and inorganic constituents of the exposome from a single low-volume sample aliquot (50 mu L of blood or 50 mg of tissue). Liquid chromatography (LC) tandem mass spectrometry (MS) and inductively coupled plasma mass spectrometry (ICP-MS) were employed to target 94 organic and 55 inorganic analytes, including food and environmental contaminants (e.g., PFAS, mycotoxins, phytoestrogens, and heavy metals) as well as hormones, trace elements, metalloids and mineral elements. In a proof-of-principle study, the workflow was applied to human placental tissue and matched umbilical cord blood plasma samples from twelve individuals.
In total, the workflow enables quantitative assessment of 66 to 71 targeted organic analytes, of which 24 to 35 were detected in the cord blood, cord plasma, or placental tissue samples studied. Moreover, it allowed for the quantification of 14 to 20 inorganic analytes, with another 16 to 29 analytes below the limit of detection in the biological samples. Moreover, non-targeted analysis (NTA) using high resolution MS further expanded the analyte coverage of the workflow.
This first-of-its-kind approach enables (semi-)quantitative analysis of trace levels of a broad range of chemical exposures from a single sample aliquot, which is particularly advantageous when sample availability is limited.
https://doi.org/10.1016/j.talanta.2026.130499

****

Cherriere, M., Barbier, G., Oger, M., Butigieg, X., Guatto, N., De Araujo, S., *et al.*
Influence of lung overload and exposure scenarios on recovery following inhalation of an alumina nanoparticle and HCl gas mixture.
Particle and Fibre Toxicology, 2026

Co-exposure to alumina nanoparticles (Al_2O_3 NPs) and hydrogen chloride (HCl) can occur in combustion-related environments, particularly in aerospace and defense sectors. While acute pulmonary toxicity of these agents has been described, the impact of temporal exposure patterns on the persistence of inflammation and the link to cumulative lung burden and clearance efficiency remains poorly understood.
Following nose-only inhalation in rats, we compared two exposure regimens to equivalent concentration ranges (1–20 mg/m³ Al_2O_3 with 5 ppm HClg) : a short-term scenario (four consecutive days) and a long-term intermittent scenario (once a week for 8 weeks). Lung burden, clearance kinetics, inflammatory responses, molecular stress markers, as well as potential longer-term impact and recovery were assessed at 1 and 28 days post-exposure. Short term scenario induced a dose-dependent neutrophilic inflammation that resolved by day 28, consistent with partial restoration of alveolar clearance. In contrast, repeated long-term scenario resulted in significantly

higher retained lung burdens, reduced clearance efficiency, and persistent neutrophilic inflammation at day 28. Surface area-based estimations indicated that the highest long-term scenario exceeded established NPs lung overload thresholds, suggesting a mechanism involving impaired clearance and sustained inflammatory signaling. Sustained parenchymal cytokine activation and altered stress-response gene expression further supported the establishment of a non-resolving inflammatory state. However, importantly, persistent inflammation was not associated with tissular damage or genotoxicity. These findings demonstrate that temporal exposure pattern is a critical determinant of lung overload and recovery capacity following inhalation of poorly soluble NPs. Repeated intermittent exposure promotes clearance impairment and persistent inflammation, underscoring the importance of dose metrics and exposure frequency in risk assessment.
https://doi.org/10.1186/s12989-026-00703-7

****

Costa, L. F., De Lima, R. J., Da Freiria, A. J. I., De Lima, O. B., Fernandes, W. R. B., Watanabe, L. H.*, et al.*
Biomonitoring to assess the pesticides exposure of rural workers : An elucidative and critical review.
Regul Toxicol Pharmacol, 2027, Vol. 173, article : 106270

The intensive use of pesticides, as in coffee production, is associated with increased health risks among rural workers. Exposure and effect biomarkers are commonly used to assess occupational exposure and potential biological effects of these chemicals. However, global frameworks for occupational risk management remain incomplete, as regulatory agencies typically recommend monitoring cholinesterase activity as a biomarker, despite many pesticides not sharing this mechanism of action.
Moreover, occupational exposure often involves complex mixtures of pesticides that are not adequately captured by cholinesterase-based monitoring alone. This study presents a critical and elucidative review highlighting the potential applicability of alternative biomarkers beyond cholinesterase inhibition. Only analytical human studies involving rural workers (n = 17), published in or after 2019 and employing biomarkers of exposure and/or effect, were included, in accordance with PRISMA statement guidelines. The review identified several potential biomarkers for monitoring pesticide exposure and highlighted the frequent use of genotoxicity assays and oxidative stress markers as effect biomarkers, which were suggestively associated with urinary levels of pesticide metabolites used as exposure biomarkers. These findings support occupational health practices, acknowledge the limitations of predominantly cross-sectional designs, encourage further research, and inform the development of more effective regulatory frameworks, contributing to improved quality of life of workers.
https://doi.org/10.1016/j.yrtph.2026.106270

****

Lallmahomed, A., Mercier, F., Costet, N., Slimani, K., Thao Dao, T. P., Pecheux, M.*, et al.*
Assessing hair for human biomonitoring : comparison of organophosphorus flame-retardant levels in hair, urine and blood from the same individuals.
Environ Int, Vol. 216, (2026), article : 110545

Total exposure assessment can be performed through biological monitoring. While blood and urine are commonly used matrices, hair represents an innovative alternative due to its ease of collection and its ability to reflect long term exposure. However, its applicability remains limited by insufficient data and unclear performance. In this study, hair, serum, and urine samples from 62 adults were analyzed for ten organophosphorus flame retardants (OPFRs). Detection frequencies, concentration levels, and relationships between matrices were evaluated using descriptive statistics, correlation, and clustering analyses. The effects of hair washing and urinary dilution corrections were also assessed.
A greater number of compounds were detected in hair (7 compounds) compared to urine (5 metabolites only) and serum (2 compounds), indicating higher sensitivity of hair for OPFR detection. Hair concentrations were independent of gender, and strongly correlated between washed and unwashed samples, although washing significantly reduced measured levels for parent OPFRs. Importantly, no significant correlations were observed between hair and urine (DPP, BCEP) or serum (TCPP), suggesting that hair reflects different exposure information rather than duplicating conventional matrices. These findings demonstrate that hair provides complementary

and more comprehensive exposure information, supporting its use alongside urine and serum to improve OPFR biomonitoring in epidemiological studies.
https://doi.org/10.1016/j.envint.2026.110545

****

Mishra, R. K., Roy, S., Mishra, A., Prakash, V., Shekhar, R., Kumar, N.*, et al.*
Multi-metal co-exposure and type 2 diabetes: integrating biomonitoring evidence, inflammatory mechanisms, and a framework for future risk stratification.
Environmental Geochemistry and Health, 2026, vol. 48 (15), article 620.

Diabetes Mellitus Type 2 prevalence is still increasing around the world, and there is growing evidence of the role of environmental co-exposures to heavy metals-cadmium, lead, arsenic, mercury, and chromium-in glycaemia impairment. Contrarily to studies on single metal toxicology, real-life situations consist in exposure to mixtures of heavy metals through environmental, occupational and dietary pathways, especially in places like the Indo-Gangetic plain of India, characterized by the presence of geological arsenic pollution in association with metals exposure.
This paper provides a narrative review on the current state of art in the domain of three key issues connected to risk stratification in Type 2 Diabetes Mellitus : methods for biomonitoring metals, inflammatory and molecular pathways involved in diabetes onset and progression related to metal exposures and statistical approaches for modeling joint effects of mixtures.
Firstly, discuss on the biomonitoring methods, with particular emphasis to blood, urine and hair and nail as classical matrices and new emerging matrices (saliva, buccal cells). The analytical technique (AAS vs ICP-MS) is considered as well. It will focus on the heterogeneity between different methodologies, including matrix-specific exposure window and inter-laboratory variability. Regarding mechanistic aspects, there is an agreement in scientific literature on several molecular pathways involved in glycaemia alterations, including oxidative stress, NF-kappa B inflammation pathway, mitochondria dysfunction, epigenetics alteration and insulin signaling impairment, with possible synergistic rather than additive action of heavy metals in the impairment of beta-cell function and insulin resistance. Finally, it discusses some recent advances in quantifying joint metal effects on diabetes through specific statistics as WQS regression and Bayesian Kernel Machine regression (BKMR) and quantile g-computation. Even though important methodological advances have been made, a translational gap remains: no validated procedure currently exists that integrates exposure metrics, inflammatory biomarkers and clinical variables for individual risk stratification.
We therefore outline a research-stage framework that could guide future development of such tools.
Graphical Abstract Integration of biomonitoring with advanced mixture-modelling approaches (WQS, BKMR, and quantile g-computation) enables cumulative exposure assessment and supports a proposed research framework for future risk stratification and precision environmental health. The pyramid represents a future validation pathway, not an established clinical tool. Created in BioRender. Mishra, R. (2026).
https://doi.org/10.1007/s10653-026-03518-9

****

The association among metals and changes in their concentrations in the treatment of lead poisoning in lead-exposed workers.

Ming, X., Wu, Y., Cao, J., Zhang, T., Cui, S., Yang, Y., et al.

Food Chem Toxicol, (2026), Vol. 218, article : 116396

BACKGROUND : High-throughput metallomics studies on lead-exposed workers are rare, and the effects of lead exposure on other metals, as well as the loss of trace metals during such treatments, remain unclear.

METHODS : We recruited 1091 lead-exposed and 75 lead-poisoned workers undergoing calcium disodium ethylenediaminetetraacetate (CaNa(2)EDTA) treatment. Urine samples were analyzed for 33 metals/metalloids using inductively coupled plasma mass spectrometry (ICP-MS). In lead-poisoned workers, first morning urine was collected daily over a 15-day two-course of lead elimination treatment, plasma metals were also measured pre- and post-treatment.

RESULTS : In the high-lead group, urinary concentrations of 22 elements-including Fe, Zn, Mg, Ca, Cd, U, and Cu-were significantly higher than in the low-lead group. During the two CaNa(2)EDTA treatment cycles, urinary concentrations of Zn, Fe, and Cd showed trends similar to those of Pb, whereas Rb showed an opposite trend; however, Cd exhibited a one-day lag effect relative to Pb. We estimated that during lead elimination therapy, additional losses of 5.11?mug/L.kg Fe, 11.71?mug/L.kg Pb, and 62.23?mug/L.kg Zn occurred per kilogram of body weight. Furthermore, plasma iron (Fe) and lead (Pb) levels decreased by 13.30% and 61.74%, respectively, following CaNa(2)EDTA treatment.

CONCLUSION : Metal elements showed significant associations in lead-exposed workers, which may reflect either metabolic interactions or co-exposure in the occupational setting. Preliminary evidence suggests a potential link between CaNa(2)EDTA treatment and increased excretion of iron (Fe) and zinc (Zn). Given this, clinicians may wish to be alert to the possibility of monitoring these elements.

DOI : https://doi.org/10.1016/j.fct.2026.116396

****

3. Approches métabolomiques

Jing, F., Wang, M., Wen, L., Liu, X., Xu, G.
Artificial intelligence-enabled mass spectrometry-based metabolomics : current status and future prospects.
Trac-Trends in Analytical Chemistry, january 2027, Vol. 206 Part B, article : 119188

Metabolomics is the study of small-molecule metabolites within living organisms, which reflects the physiological and pathological states of a biological system at a specific time. High resolution mass spectrometry (HRMS) is one of the most useful tools for untargeted metabolomics analysis. Although great advances have been achieved, many challenges still exist in peak matching and batch effects for a large number of samples, structural annotation and identification of features, and reproducibility and standardization etc.
In this perspective, we review the advances and limitations of current metabolomics with a primary focus on biomedical applications, summarize artificial intelligence (AI)-enabled metabolomics, and propose a new framework of the "Third-generation metabolomics". The latter approach, by integrating automated instruments with AI, enables standardization, streamlined workflow, automation, and intelligent operations. Based on this, AI-based "Lights-Out" laboratories will provide high-quality data which is helpful to construct "Metabolome-centered Digital Twins" and promote the transition from descriptive phenotyping to predictive simulation, thereby providing a basis for precision medicine and a systemic understanding of biological complexity.
https://doi.org/10.1016/j.trac.2026.119188

****

Moufawad, T., Ayeni, K., Baira, E., Baudry, C., Belova, L., Chaker, J.*, et al.*
Comparing Suspect and Nontargeted Screening Workflows for Perinatal Chemical Exposome Analysis : A European Interlaboratory Study from the PARC-EU Project.
Environmental Science & Technology, 15 septembre 2026, 60 (38) : 26987–27000.

Early-life chemical exposures may contribute to adverse health outcomes later in life. However, conventional chemical analyses typically cover only a limited subset of the chemical exposureome. Suspect and nontargeted screening (SS/NTS) using high-resolution mass spectrometry (HRMS) workflows provides a powerful framework for comprehensive assessments of exposure, with the potential to detect a broad range of environmental contaminants and emerging chemicals.
An interlaboratory assay involving 12 laboratories was performed to evaluate the comparability and complementarity of SS/NTS approaches for maternal urine, serum, and milk, based on reversed-phase (RPLC), hydrophilic interaction liquid chromatography (HILIC), and gas chromatography (GC) with HRMS. Participants used in-house methods to possibly detect a predefined and shared list of 50 compounds with varying polarities spiked at three concentrations. The overall detection rates ranged from 4% to 72% for all three techniques, with RPLC-HRMS covering compounds with log P 0–6, while HILIC-HRMS and GC-HRMS extended this coverage.

Univariate and multivariable analyses of RPLC-HRMS results for serum and urine identified sample preparation steps as key factors influencing detection rates. Workflow performances were additionally benchmarked by using the S-score.
These findings demonstrate the complementarity of SS/NTS platforms for extending chemical-space coverage for the most comprehensive exposure characterization.
Therefore, efforts should be made for harmonized QA/QC provisions while conserving the added value of different workflows for exposure data for risk assessments.
https://doi.org/10.1021/acs.est.6c04347

****

4. Modèles, outils de mesures

Bertrand, N., Bouvet, D., Passeron, J., Vandevondele, C., Pham, C., Patrascu, C.
Anticiper et surveiller les pathologies émergentes liées aux poly-expositions chimiques. Approche comparée d'un service interentreprises (AMETRA06) et autonome (AIRBUS).
Archives des Maladies Professionnelles et de l'Environnement, 2026, Vol. 87 (3-4), article : 103316.

L'exposition professionnelle au risque chimique est par nature multiple : solvants, poussières, fumées de soudage, biocides ou principes actifs s'entrecroisent selon les tâches effectuées et les procédés. Ces mélanges complexifient l'évaluation des risques, car ils peuvent exacerber la toxicité par des effets d'additivité ou de synergie, favorisant des pathologies respiratoires, cutanées, neurologiques, reprotoxiques ou cancérogènes. L'adoption d'une approche intégrant la poly-exposition est cruciale : elle permet d'identifier 20 % de situations à risque supplémentaires (Clerc 2018) par rapport à une analyse mono-substance.
https://doi.org/10.1016/j.admp.2026.103316

****

5. Polyexpositions aux métaux lourds

Effets sur la santé

5.1 Effets neurologiques et santé mentale

Assessment of anxiety risk association with PAHs and aluminum co-exposure in an aluminum production facility.

Zare, M. R., Kakhaki, H. E. S., Zare, M., Ahmadi, M. S., Ardakani, M. B.

Journal of the Egyptian Public Health Association, 2026, Vol. 101 : 27

Background Workers in aluminum production plants are occupationally exposed to polycyclic aromatic hydrocarbons (PAHs), including the neurotoxicant benzo[a]pyrene (BaP), as well as to aluminum dust and fumes. While the physical health effects are established, the psychological impact, particularly on anxiety, remains less explored. This study investigated the associations of urinary 1-hydroxypyrene (1-OHP), a biomarker of PAHs exposure, and urinary aluminum levels with anxiety symptoms in aluminum workers.

Methods In this cross-sectional study, 260 participants (130 exposed workers and 130 controls) from an aluminum plant were enrolled. Urinary aluminum concentration was measured using inductively coupled plasma mass spectrometry (ICP-MS). Anxiety was assessed using the Beck Anxiety Inventory (BAI), and job stress was evaluated using the Job Content Questionnaire (JCQ). BaP exposure was assessed using personal air sampling following NIOSH Method 5515. Urinary 1-OHP levels were quantified using high-performance liquid chromatography (HPLC). Group comparisons, Pearson correlation, and multiple linear regression analyses were performed using SPSS software version 22.

Results The exposed group had significantly higher anxiety scores (10.74 +/- 6.18) than the control group (8.88 +/- 5.28). Urinary aluminum concentration was significantly higher in the exposed group (33.45 +/- 16.20 & micro;g/g creatinine) compared to controls (7.35 +/- 3.99 & micro;g/g creatinine). In the final regression model, which included total job stress as an independent variable alongside age, job experience, and smoking, urinary 1-OHP (beta = 0.204), urinary aluminum (beta = 0.177), smoking (beta = 0.202), and total job stress (beta = 0.295) were all significantly associated with anxiety, explaining 38.4% of the variance (R & sup2; = 0.384).

Conclusion The internal dose of PAHs, measured via urinary 1-OHP, and aluminum body burden, measured via urinary aluminum, are significantly associated with higher anxiety symptoms. Notably, job stress also independently was associated with anxiety in this cohort. This highlights the potential neurotoxic impact of combined PAH and aluminum exposure on mental health and suggests the need for integrated psychological and biological monitoring in high-risk occupations.

DOI : https://doi.org/10.1186/s42506-026-00233-2

****

Cumulative and Interactive Effects of Heavy Metal Mixtures Across Neurodegenerative Diseases : A Comparative Review of Alzheimer, Parkinson, Amyotrophic Lateral Sclerosis and Multiple Sclerosis.

Mitu, I., Caba, I., Macovei, I.

Journal of Xenobiotics, 2026, Vol. 16 (5), 174.

Heavy metals and metalloids are persistent environmental contaminants that accumulate in the central nervous system and interact with endogenous essential metals, yet most neurotoxicological research continues to treat metals as independent agents rather than as co-occurring mixtures.

This review systematically compares the evidence for cumulative and interactive effects of heavy metal mixtures across four major neurodegenerative diseases-Alzheimer's disease (AD), Parkinson's disease (PD), amyotrophic lateral sclerosis (ALS), and multiple sclerosis (MS)-asking which metal combinations have been directly documented for each disease, and whether these patterns are disease-specific or shared. Following a PubMed search (January 2016-June 2026), 93 unique studies were included (AD: 49; PD: 38; ALS: 19; MS: 18; 31 shared across diseases).

Combined exposure to lead, cadmium, arsenic, and mercury is linked to amyloid-beta accumulation and dementia risk in AD; manganese-vanadium co-exposure produces more severe dopaminergic damage in PD than either metal alone, with manganese activating the familial PD gene LRRK2; a multi-metal mixture in ALS was associated with a three-fold higher disease risk independent of genetic susceptibility; and MS showed almost no designed mixture studies despite considerable single-metal data, with conflicting findings across cohorts.

Three general mechanisms were identified: competition at shared membrane transporters (notably DMT1), sequestration by metal-binding proteins, and direct synergistic or antagonistic interactions, in which essential elements can modulate toxic-metal handling. Mixture-statistics approaches (WQS, BKMR), already established for AD and PD, should be extended to MS to close this evidence gap.

DOI : https://doi.org/10.3390/jox16050174

****

5.2 Effets rénaux – Néphrotoxicité

Association of mixed metal exposure with kidney injury and benchmark dose estimation in Chinese adults aged 40 years and older.

Dai, X., Bai, Y., Qin, M., Ma, M., Zhang, Y., Song, Z., et al.

Ecotoxicology and Environmental Safety, 2026, Vol. 324, article : 120829.

Mixed exposure to metal elements is associated with an increased risk of kidney injury, but the underlying mechanism remains rather complex, making risk assessment difficult. We selected 842 adults aged between 40 and 75 from Sichuan Province, and concentrations of eight metals (Mg, Ca, Fe, Zn, As, Cd, Cu, Pb) were measured

in blood and urine. Weighted quantile sum (WQS) regression, Bayesian kernel machine regression (BKMR), and explainable machine learning (ML) approaches were integrated to systematically evaluate the associations between metal mixtures and kidney injury.

The mediating effect model and benchmark dose (BMD)/benchmark dose lower bound (BMDL) analysis were then used to estimate the risk thresholds for individual and combined exposure of key metals.

The results showed that blood metal mixtures were significantly and positively associated with kidney injury risk, driven primarily by Cd and Pb. BKMR analysis revealed that there was a synergistic relationship between Cd-Pb and Cd-Fe, while there was an antagonistic relationship between Ca-Cd. Explainable ML revealed that Zn has an antagonistic effect on Cd/Pb, while Ca/Zn has a certain protective effect. Mediation analysis revealed that mALB and beta 2-MG were potential mediating factors in the association between cadmium/ lead exposure and chronic kidney disease. Beta 2-MG exhibited a more stable indirect effect.

The BMD results showed that among the total population, the BMDL05 value of urinary lead was the lowest (0.44 mu g/g Cr). These results provide a quantitative basis for the risk prevention and health standard setting of mixed metal exposure in the middle-aged and elderly population.

DOI : https://doi.org/10.1016/j.ecoenv.2026.120829

****

Multi-level evidence for Pb-Cd co-exposure nephrotoxicity: An integrated analysis of NHANES, outcome-oriented network toxicology, and cell-based validation.

Tang, Y., Li, C., Liu, M., Li, N., Liu, B., Li, D., et al.

Ecotoxicol Environ Saf, (2026), Vol. 323, 120747.

BACKGROUND: Lead (Pb) and cadmium (Cd) remain widespread environmental toxicants, and the kidney is a major target organ. However, reliance on a single biomarker matrix or renal endpoint may incompletely characterize Pb-Cd-associated renal abnormalities. Whether blood- and urine-based Pb/Cd biomarkers exhibit differential association profiles across renal outcomes, and whether outcome-oriented networks converge on shared candidate pathways, remains unclear.

METHODS: We analyzed NHANES 2011-2018 data from 5049 adults. Blood and urinary Pb and Cd biomarkers were evaluated in relation to estimated glomerular filtration rate (eGFR), albuminuria [log(UACR)], and a CKD-compatible phenotype using survey-weighted regression, whereas Pb-Cd mixtures were examined using case-weighted quantile g-computation and generalized weighted quantile sum regression. Effect modification by age, sex, BMI, diabetes, and hypertension was evaluated using formal interaction tests with false-discovery-rate correction. An outcome-oriented network toxicology framework was constructed using CKD-, albuminuria-, and broad renal injury-oriented disease modules. HEK293T cells were used for targeted cellular assessment of cytotoxicity, intracellular metal accumulation, redox and inflammatory responses, and transcriptional changes in genes prioritized by network analysis following Pb, Cd, or combined exposure. Exploratory molecular docking was performed to examine potential metal-protein interaction sites.

RESULTS: Individual-biomarker and mixture analyses showed that the observed associations varied across biomarker matrices and renal outcomes. Urinary Pb was positively associated with eGFR; urinary Cd and blood Pb were associated with higher log(UACR); and blood Pb and blood Cd were associated with higher odds of the CKD-compatible phenotype. The urinary Pb-Cd mixture was positively associated with eGFR and log(UACR), whereas the blood mixture was associated with higher log(UACR) and higher odds of the CKD-compatible phenotype. Formal interaction analyses identified age-related heterogeneity in selected blood-based associations, while inverse associations of blood Pb, blood Cd, and urinary Cd with eGFR were stronger among participants with diabetes. Outcome-oriented network analysis consistently prioritized IL1B and IL6 as shared inflammatory hubs, while peripheral network architecture differed across renal modules. In HEK293T cells, combined Pb-Cd exposure increased intracellular metal burden and cytotoxicity, reduced antioxidant capacity, and altered the expression of IL1B, IL6, and selected stress-response genes.

CONCLUSION: Blood- and urine-based Pb and Cd biomarkers exhibited distinct association profiles across renal outcomes, indicating that a single biomarker matrix or endpoint may incompletely characterize Pb-Cd-associated renal abnormalities. Outcome-oriented networks converged on IL1B and IL6 as shared inflammatory hubs within distinct peripheral architectures, with targeted cellular evidence supporting the responsiveness of

prioritized targets. These findings establish an integrative, multi-matrix and multi-outcome framework for the mechanistic interpretation and risk assessment of Pb-Cd co-exposure.

DOI : https://doi.org/10.1016/j.ecoenv.2026.120747

****

Zulian, E., Barbiero, F., Zanette, M., Mauro, M., Miani, A., Larese Filon, F.
Biological chromium and nickel monitoring in metalworkers : welders versus non-welders.
Occupational Medicine, 2026 ; kqag126

BACKGROUND: Welding fumes contain toxic metals, such as chromium (Cr) and nickel (Ni), which pose long-term health risks, including chronic respiratory diseases and cancer. Tungsten inert gas (TIG) welding of stainless steel generates ultrafine particles of these metals. Evidence on urinary concentrations in welders is limited. AIMS: To assess urinary Cr and Ni concentrations in male metalworkers, according to job role and smoking habits and evaluate associations with exceeding ACGIH biological limit values (Cr: 0.7 mug/l; Ni: 5 mug/l).
METHODS: In this cross-sectional study, 245 male metalworkers from Friuli Venezia Giulia were recruited, including 179 welders and 66 non-welders. Demographics and smoking history (pack-years) were collected during annual health surveillance. End-of-week urine samples were analysed for Cr and Ni using inductively coupled plasma mass spectrometry. Group differences were tested with non-parametric methods. Logistic regression estimated adjusted odds of exceeding biological limits. RESULTS: Welders had higher median urinary Cr and Ni than non-welders (0.75 versus 0.56 mug/l; P = 0.020 and 1.70 versus 1.10 mug/l; P = 0.0001, respectively. Half of the subjects (50.0%) exceeded the Cr limit. Welding was associated with a borderline higher odds of exceeding the Cr limit (OR = 1.71; 95% CI 0.96-3.06; P = 0.070). Age and smoking were not related to exceeding limits.
CONCLUSIONS: Welders are exposed to higher urinary Cr and Ni levels than non-welders, with stronger associations for Cr. Findings support the need for preventive intervention and targeted biomonitoring, particularly in TIG stainless steel welding.
https://doi.org/10.1093/occmed/kqag126

****

5.3 Effets inflammatoires et stress oxydatif

Association Between Metal Mixtures and C-Reactive Protein Levels : A Study Based on Occupational Populations in China.

Zhang K, B. S., Soontornchai S, Yang X

Biol Trace Elem Res., Vol. 204 (11), (2026), 8328-8336.

This study aimed to systematically investigate the relationship between mixed heavy metal exposure and serum C-reactive protein (CRP) level using an integrated multi-model statistical strategy.

This study included 568 participants from the Manganese-Exposed Workers Healthy Cohort. Serum CRP and 20 blood metal concentrations were measured. Key metals were selected via LASSO regression and overall mixture effects and metal contributions were quantified by Quantile g-computation; and joint effects, nonlinearity, and interactions were evaluated using Bayesian Kernel Machine Regression (BKMR). LASSO regression identified 9 key metals (Calcium, Nickel, Copper, Titanium, Tin, Vanadium, Selenium, Arsenic, Rubidium). GLM revealed inverse linear associations for Ca, Se, Rb, and Ni, and a positive association for Cu with CRP. Quantile g-computation showed the overall mixture was significantly inversely associated with CRP (HR = 0.955, 95% CI: 0.918, 0.996), with calcium contributing the largest negative weight (-0.31). BKMR indicated that the overall mixture effect showed a monotonic decreasing trend across exposure quantiles, with a significant positive association at lower quantiles (0.25-0.5). BKMR also identified a significant positive interaction for tin (posterior mean = 0.051, 95% CI: 0.004, 0.098), with calcium showing the highest posterior inclusion probability (PIP = 0.972).

This study suggests that metal mixtures exert exposure-level-dependent effects on CRP with complex interactions. Calcium may act as a central regulator, while tin shows amplified effects at higher co-exposure levels. These findings advance mechanistic understanding of mixture toxicology and inform exposure-level-specific risk assessment.

Keywords: C-reactive protein; Environmental epidemiology; Metal mixture; Occupational population.

DOI : https://doi.org/10.1007/s12011-026-05261-9

****

Occupational metal exposure and systemic inflammation among recycling workers engaged in domestic waste sorting, shredding, and material extraction.

Hansen, K. K., Schlunssen, V., Ostergaard, K., Lundh, T., Sigsgaard, T., Madsen, A. M., et al. Ann Work Expo Health, (2026), Vol. 70 (8), wxag090

INTRODUCTION: The amount of metal-containing waste being recycled and the number of employees in these recycling industries, an important part of the green transition, are increasing. It is essential to ensure that the workers are not exposed to harmful levels of metals during work. This study aims to document current biomarker exposure levels of metals and investigate the association between metals and inflammatory biomarkers among recycling workers.

METHODS: In this cross-sectional study, concentrations of lead, mercury, copper, cobalt, cadmium, chromium, manganese, nickel, and selenium were measured in urine pre-shift and whole blood post-shift among 101 recycling workers from 12 companies mainly recycling domestic waste. Serum concentrations of inflammatory markers (CRP, SAA, CC16, IL1B, IL2, IL4, IL5, IL6, IL8, IL10, IL13, and TNF) were measured. Associations between metal levels by work task, waste fractions, and inflammatory markers were explored by linear mixed-effects models.

RESULTS: Overall, we observed no substantial differences in metal concentrations between production and administrative workers. However, nickel and lead blood levels, and mercury urine levels were highest among workers handling metal and electronic/hazardous waste. Compared to administrative workers, metal levels were in adjusted analysis increased in some job tasks (nickel for paper/cardboard; lead and cadmium for plastic/biowaste/metals; mercury for electronics/hazardous waste handling). After adjusting for potential confounders, including endotoxins, increasing lead, nickel, and copper blood levels were associated with increasing concentrations of CRP, SAA, IL1B, IL8, and/or TNF.

CONCLUSIONS: We found overall no increased levels of metals among recycling workers. However, the highest levels of metals were found among workers handling metal and electronics/hazardous waste. Nickel, lead, and copper in blood were associated with increased inflammatory markers, but for other metals the associations were less clear. The findings highlight metal exposure from specific waste fractions and underscore the need for further research on potential health effects in the growing recycling industry.

DOI : https://doi.org/10.1093/annweh/wxag090

****

Chromium and lead levels and their health effects on welding and electroplating exposed workers : A pilot study.

Cedillo Alvarez, C., Bravo Gomez, M. E., Montes, S., Romo Magdaleno, J. A., Barrios Melendez, G., Trujillo Garcia, A., et al.

J Occup Environ Hyg, (2026), 1-13.

Some industrial activities involve worker exposure to chromium (Cr) and lead (Pb). This study aimed to correlate blood and urine levels of Cr and Pb in welding and electroplating workers with health effects, including plasma lipid peroxidation and biochemical parameters.

Physical examinations and health questionnaires were conducted on 33 exposed workers and 39 control subjects. Blood chromium (CrB), lead (PbB), malondialdehyde (MDA) levels, and standard biochemical

parameters were analyzed. The exposed group exhibited higher blood levels of MDA, Pb, and Cr compared to the control group.

Among exposed workers, rhinorrhea, nasopharyngeal itching, and hyperemia were the most commonly reported signs and symptoms. CrB levels were found to negatively correlate with platelet count, glucose, MDA, and bilirubin. Blood lead (PbB) levels showed a correlation with glucose, while urinary lead (PbU) levels were associated with glucose and MDA. Despite the relatively low levels of Cr and Pb detected in blood, metal-exposed workers demonstrated health issues.

DOI : https://doi.org/10.1080/15459624.2026.2709625

****

5.4 Effets génotoxiques et cancérogènes

Exposure to metal mixtures and micronuclei frequency among occupational populations : Association analysis, benchmark dose estimation, and network toxicology.

Wang, Y., Pang, Y., Zhao, X., Wu, X., Han, K., Liu, X., et al.

Ecotoxicol Environ Saf, 2026, Vol. 324, article : 120810.

BACKGROUND: Few studies have investigated the associations between mixed metal exposure and genetic damage, and determining the benchmark dose for metals in urine based on micronuclei (MN) frequency.

OBJECTIVE: To analyze the associations between metal mixtures in urine and micronuclei frequency, estimate the benchmark dose (BMD) and lower confidence limit (BMDL), and explore potential biological pathways using network toxicology.

METHODS: A total of 578 participants were recruited from a large lead smelting plant. The concentrations of 16 metals in urine were measured using inductively coupled plasma mass spectrometry (ICP-MS). Cytokinesis-block micronuclei (CBMN) assay was performed to detect the frequency of micronuclei (MN). Negative binomial regression (NBR), weighted quantile sum (WQS) regression, and Bayesian kernel machine regression (BKMR) were used to analyze the associations between urinary metals and MN frequency, pinpoint key contributors, as well as interactions among metals. Three BMD software were utilized to estimate the BMD and BMDL for metals in urine. Additionally, network toxicology analysis was carried out employing CTD, GeneCards, STRING, Cytoscape, along with GO and KEGG enrichment analyses to predict potential pathways linking lead (Pb), cadmium (Cd) and arsenic (As) exposure with MN frequency.

RESULTS: The distribution of urinary metals concentrations was skewed, with medians (P(25), P(75)) being 9.53 (4.67, 19.48) for Pb, 1.64 (0.92, 2.98) for Cd, 31.36 (19.54, 50.03) for As, and 2.55 (0.77, 4.71) mug/g creatinine for Ba. The average level of MN frequency was (1.22?+/-?1.41) per thousand for all participants, with values of (3.60?+/-?1.01) per thousand for the elevated MN group and (0.67?+/-?0.76) per thousand for the normal MN group (t?=?-33.658, P?<?0.001). Both the NBR and WQS models indicated that Pb, Cd, As and Ba were significant contributors to MN frequency. The BKMR model revealed positive associations between the mixtures of urinary metals and the MN frequency, highlighting potential interactions among Pb and Cd, As and Cd, as well as Ba and Cd that could elevate the micronuclei rate. The BMDs and BMDLs were 1.425 and 0.485 for Pb, 0.199 and 0.041 for Cd, 7.661 and 3.678 for As, and 0.435 and 0.003?mug/g creatinine for Ba. Network toxicology analysis identified 315 candidate target genes, and GO and KEGG enrichment analyses identified potential pathways related to oxidative stress, inflammatory responses, apoptosis, and cellular senescence.

CONCLUSION: The metal mixtures in urine were positively associated with the frequency of micronuclei, with Pb, Cd, As, and Ba being the key contributing factors. The BMD and BMDL for these urinary metals could serve as a preliminary reference for genetic damage risk assessment. Exploratory network toxicology indicated that genetic damage associated with Pb, Cd and As exposure may involve pathways related to oxidative stress, inflammation, apoptosis, and aging.

DOI : https://doi.org/10.1016/j.ecoenv.2026.120810

****

Combined Exposure to Safe-Level Metals Drives Potent and Persistent Oncogenic NRF2 Activation.

Wang, Z., Liu, Z., Boffetta, P., Yang, J., Clouston, S., Meliker, J., et al.

SSRN, (2026), 38 p.

Chronic exposure to complex mixtures of environmental contaminants is ubiquitous, yet current regulatory and scientific frameworks largely evaluate individual toxicants in isolation, potentially underestimating the carcinogenic risks posed by combined exposures.

Here, we demonstrate that environmentally relevant mixtures of arsenic (As^{3+}), cadmium (Cd), and lead (Pb) elicit cooperative oncogenic responses that cannot be predicted from their individual effects. Among a broad panel of stress-responsive transcription factors, Nrf2 exhibited a uniquely rapid and persistent response to (As^{3+}) exposure. Notably, an equitoxic (As^{3+})-Cd-Pb mixture produced additive and synergistic Nrf2 activation at concentrations relevant to human exposure. Integrative transcriptomic, ChIP-seq, and Hi-C analyses identified Nrf2 as a convergent regulator of mixed-metal responses while revealing distinct metal-specific transcriptional programs. Mechanistically, metal-induced Nrf2 activation remodeled higher-order chromatin architecture, including reorganization of the metallothionein locus and formation of a previously absent sub-TAD at the KLF4 locus.

This Nrf2-dependent chromatin reorganization promoted long-range interactions between an upstream super-enhancer and the KLF4 promoter, providing a 3D genomic mechanism for oncogenic KLF4 activation. Consistent with these regulatory changes, mixed-metal exposure synergistically induced oncogenic and cancer stemness-associated programs involving epithelial-mesenchymal transition (EMT), metabolic reprogramming, proliferation, inflammation, and extracellular matrix remodeling. Together, these findings establish Nrf2 as a central mechanistic link between environmental metal mixtures, 3D genome reorganization, and persistent oncogenic signaling. More broadly, they demonstrate that combined exposures can amplify carcinogenic responses at otherwise low concentrations, challenging single-contaminant risk assessment paradigms and suggesting that environmental mixtures may effectively lower the carcinogenic threshold of individual metals.

DOI : https://doi.org/10.2139/ssrn.7565093

****

5.5. Vieillissement biologique

Associations of single and combined exposure to plasma metals with biological aging in Chinese adults : Mediation by inflammation and oxidative stress and moderation by diabetes.

Liang, X., Liu, S., Huang, Y., Zheng, Y., Li, L., Peng, Z., et al.

Journal of Hazardous Materials, 2026, Vol. 517, article : 143662

This cross-sectional study examined the single and combined associations of plasma metals with biological aging and explored the potential mediating roles of inflammation and oxidative stress, as well as the modifying effect of diabetes.

Seventeen plasma metals and four biological age acceleration metrics (KDM_accel, PhenoAge_accel, PAI_accel, and homeostatic dysregulation (HD)) were assessed in 3055 Chinese volunteers. Generalized linear model, generalized additive model, least absolute shrinkage and selection operator, weighted quantile sum (WQS), quantile g-computation (qgcomp), and Bayesian kernel machine regression (BKMR) were employed to evaluate individual and combined effects. Plasma Cu and Sr showed positive associations with at least two aging indicators, whereas V, Fe, and Zn were negatively associated with aging. The metal mixture consistently exhibited linear and positive associations with KDM_accel and HD (predominantly driven by Cu, Se, and Sb), as revealed by WQS, qgcomp, and BKMR.

Meanwhile, the metal mixture showed complex nonlinear relationships with PhenoAge_accel and PAI_accel. Cu and Co were the primary positive contributors to PhenoAge and PAI, whereas V and Fe were the primary negative contributors. Inflammation and oxidative stress were found to partially mediate the associations between metals and aging.

Additionally, diabetes, a metabolic disease accompanied by inflammation and oxidative stress, was related to accelerated aging and significantly modified the metal-aging relationships.

These findings suggest that exposure to metals is associated with biological aging, with dose-response patterns depending on the specific metal and aging indicator. Future prospective research is necessary to confirm these associations and further elucidate the roles of inflammation, oxidative stress, and diabetes in metal-aging associations.

DOI : https://doi.org/10.1016/j.jhazmat.2026.143662

****

6. Multiples expositions aux polluants ambiants, VOCs, pesticides

SMARGIASSI A. ; DEBIA M. ; SUARTHANA E.

Effets respiratoires de l'exposition journalière aux particules respirables, fines et ultrafines dans divers milieux de travail.

Rapport scientifique. RS-1235-fr, Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST), Montréal (Canada), 2026, 11 p., ill., bibliogr. (En français)

Bien que de nombreux travailleurs soient quotidiennement exposés à de fortes concentrations de particules respirables, peu d'études analysent l'impact de cette exposition à court terme sur leur appareil respiratoire, la recherche privilégiant généralement les effets à long terme. Ce projet de recherche visait à caractériser l'exposition journalière de travailleurs à ces particules ainsi qu'à leur potentiel oxydatif (PO), tout en évaluant leurs répercussions immédiates sur la fonction respiratoire et l'inflammation pulmonaire.

La méthodologie repose sur le suivi répété pendant cinq jours d'une cinquantaine d'apprentis de la construction, complété par une revue systématique de la littérature scientifique comparant les données des travailleurs à celles de la population générale. Les résultats démontrent que la charge oxydative varie fortement d'un secteur à l'autre : à concentration égale, les particules de soudage s'avèrent nettement plus oxydantes que celles du briquetage ou de la menuiserie. Chez les apprentis suivis, l'augmentation de l'exposition aux poussières respirables et oxydantes est directement corrélée à une hausse des marqueurs de l'inflammation respiratoire. Toutefois, la synthèse bibliographique révèle un paradoxe : à exposition équivalente, la baisse de la fonction respiratoire chez les travailleurs est dix fois inférieure à celle observée dans la population générale. Cet écart s'explique par la composition physico-chimique distincte des particules en milieu professionnel, ainsi que par un biais de sélection de type « travailleur sain », les jeunes apprentis affichant une condition physique supérieure à la moyenne.

En conclusion, l'étude confirme l'impact délétère de l'exposition quotidienne aux particules sur la santé pulmonaire et souligne la nécessité de mettre en place des mesures rigoureuses de contrôle des émissions à la source. Limiter l'exposition aux particules les plus oxydantes est indispensable pour prévenir l'inflammation pulmonaire aiguë et éviter qu'une répétition de ces épisodes ne bascule vers des pathologies chroniques.

Référence INRS-Biblio : 770419

Lien vers l'article : https://pharesst.irsst.qc.ca/expertises-revues/176/

Site de l'éditeur : https://www.irsst.qc.ca/

****

Chen, C., Xie, X., Shen, P., Liu, T., Song, F., Zhu, M.*, et al.*
Association of indoor multiple airborne pollutants co-exposure and typical respiratory symptoms among gym employees : A nationwide observational study in China.
Environ Pollut, 2026, Vol. 410, 129141.

Gym employees are exposed to pollutants in indoor gyms, but evidence on the combined effects of multiple pollutants remains limited. This observational study examined the associations of co-exposure to PM(2.5), PM(10), total fungal count (TFC) and total plate count (TPC) with respiratory symptoms among employees in 280 gyms across 32 provinces of China (2022-2023).
The median concentrations of PM(2.5), PM(10), TFC, and TPC were 35.00 mug/m(3), 59.00 mug/m(3), 170 CFU/m(3), and 226 CFU/m(3), respectively. 22.13% of employees self-reported respiratory symptoms. PM(2.5) (OR = 2.31), PM(10) (OR = 2.19), TFC (OR = 1.17), and TPC (OR = 1.24) were positively associated with respiratory symptoms (P < 0.05).
Notably, the co-exposure to four pollutants was positively associated with respiratory symptoms using the Quantile g-computation model (OR = 1.70), with PM(2.5) and TFC as the main components (P < 0.05). Protective factors included natural ventilation (OR = 0.36) and high-efficiency filters (OR = 0.42), whereas lack of equipment disinfection (OR = 3.30) and use of air-return air-conditioning systems (OR = 2.85) increased risk of respiratory symptoms (P < 0.05).
Among four potential indices, including the Fuzzy Synthetic Index, Comprehensive Evaluation Index, I(1) Index, and Indoor Air Quality Index, the I(1) Index showed a consistent positive association with respiratory symptoms across all grades (OR 2.40-3.05, P < 0.05).
Despite limitations inherent to the cross-sectional design and self-reported respiratory data, our findings provide nationwide evidence on the respiratory health of airborne pollutant co-exposure in gyms and underscore the role of integrated ventilation, air-conditioning maintenance, and hygiene management strategies for reducing respiratory symptoms among employees.
https://doi.org/10.1016/j.envpol.2026.129141

****

Gerritse, M., Boekhorst, J., Fernandes, A., Kokota, A., Vellalara, O., Huss, A.*, et al.*
Effects of commonly used pesticides and their mixtures on the upper airway epithelium using porcine organoid-derived models.
Environment International, 2026, Vol. 216, article : 110524.

Airborne pesticide contamination can result in widespread respiratory exposure particularly among agricultural workers, yet its impact on respiratory health remains poorly understood.
In this study, we assessed the effects of ten commonly used pesticides and the synergist piperonyl butoxide, individually and in mixtures, on the viability of porcine proximal airway epithelial organoid-derived monolayers. Eight of the eleven compounds reduced cell viability, with pendimethalin, glyphosate, cyprodinil and piperonyl butoxide inducing pronounced effects at low concentrations. Mixture exposure caused stronger reductions in viability than individual compounds, consistent with additive toxicity. Transcriptomic analysis of seven selected compounds revealed alterations in pathways related to epithelial barrier integrity, immune signalling, and mucociliary function.
These findings indicate that pesticide exposure of the upper airway may impair airway epithelial function and could contribute to respiratory dysfunction, highlighting the need to incorporate inhalation exposure and mixture effects in pesticide risk assessment. Moreover, this study provides a basis for the development of physiologically relevant models and targeted assays to evaluate respiratory effects of environmental pesticide mixtures.
https://doi.org/10.1016/j.envint.2026.110524

****

He, K., Zhao, S., Ma, J., Tian, L., Lai, S., Li, J.*, et al.*
PM2.5-bound plastic and rubber polymers from waste treatment facilities : Occurrence profiles and evidence of co-exposure to flame retardants.
Journal of hazardous materials, 2026, Vol. 517, article 143530.

Atmospheric PM2.5-bound plastic and rubber polymers are increasingly recognized as emerging contaminants amid concerns about inhalation exposure and potential health effects, yet their occurrence at waste treatment facilities remains poorly characterized.

This study quantified 12 target polymers in PM2.5 samples collected from four waste treatment facilities (landfill, waste incineration plant, plastic recycling plant, and wastewater treatment plant) and an urban reference site using pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS). Median total polymer concentrations followed: plastic recycling plant (8560 ng/m3) > landfill working area (964 ng/m3) > waste incineration plant (930 ng/m3) > wastewater treatment plant (646 ng/m3) > urban reference site (520 ng/m3). Polypropylene (PP) dominated at the plastic recycling plant (28-56%), while polyethylene (PE) predominated elsewhere (39-83%). Concentrations of 14HFRs at the plastic recycling plant ranged from 5.07 to 12.9 ng/m3 and were significantly correlated with PP ($r = 0.75-0.86$, $p < 0.05$), indicating their co-occurrence in workshop air. Estimated inhalation intake of PM2.5-bound target polymers for workshop workers (49.7-151 mug/day) substantially exceeded that for the general population, indicating elevated occupational inhalation exposure.
These findings reveal facility-specific differences in atmospheric polymer profiles and potential co-exposure to plastic-associated chemicals, supporting targeted monitoring and occupational exposure management at waste treatment facilities.
https://doi.org/10.1016/j.jhazmat.2026.143530

****

Palmont, P., Carsique, M., Angeli, K., Mckeon, H. P., Mienne, A., Spyropoulou, A.*, et al.*
Mixture risk assessment of pesticides with acute neurotoxic effects : a novel approach based on urinary exposure biomarkers.
Environ Int, 2026, Vol. 216, article 110531.

Pesticides showing neurotoxic effects, including organophosphates, pyrethroids, and N-methyl carbamates, are widely used in agriculture. Human biomonitoring (HBM) integrates exposure from multiple sources and routes by measuring pesticide levels in human biological samples.
This study applied a novel MRA methodology using urinary biomarkers, focusing on two cumulative assessment groups (CAGs) of pesticides with acute neurotoxic effects, as previously established by the European Food Safety Authority (EFSA), namely, CAG-NAN on brain and/or erythrocyte acetylcholinesterase inhibition; and CAG-NAM on functional alterations of the motor, sensory and autonomic division. Available urinary pesticide metabolites were assigned to potential parent compounds within these CAGs and were converted to external exposure levels, expressed as estimated daily intakes (EDI), using reverse dosimetry. Toxicological reference points, i.e., no observed adverse effect levels (NOAEL) were obtained from EFSA report. For each parent compound, the ratio of the NOAEL to the EDI was calculated, and these ratios were used to determine the total margin of exposure (MOET). This approach was applied as a proof-of-concept to children and adults from 10 HBM studies across seven European countries. For CAG-NAN, median MOET ranged between 27 and 2485 across datasets with percentage of individuals below a threshold of 100 from 2.8 to 97%. For CAG-NAM median MOET values ranged from 34 to 220 000 and in one scenario the percentage of individuals below the threshold was between 24% for children and up to 93% for adults. Azinphos-ethyl, triazophos, omethoate, and chlorpyrifos were identified as risk drivers.
This study highlights the need for improved MRA methodologies based on HBM data, including the development of pesticide-specific exposure biomarkers, and the establishment of human biomonitoring-guidance values (HBM-GVs). Incorporating HBM data strengthens human health MRA by reducing uncertainty surrounding non-dietary exposure and generating valuable evidence to inform future pesticide monitoring and regulatory strategies.
https://doi.org/10.1016/j.envint.2026.110531

****

Luo, N., Li, G., Gao, Y., An, T.
Component-specific effects shape shifts between synergism and antagonism in organophosphate ester mixtures.
Journal of Hazardous Materials, 2026, Vol. 518, article : 143996

Organophosphate esters (OPEs) frequently co-occur in human exposure, yet their combined hazards cannot be reliably inferred from single-compound toxicity. How individual OPEs reshape non-additive effects across

compositions and effect levels remains unclear.
Here, we investigated interaction patterns and associated biological responses of representative OPE mixtures, including tributyl phosphate (TNBP), triphenyl phosphate (TPHP), and tris(1,3-dichloro-2-propyl) phosphate (TDCIPP), using human keratinocytes as a dermal exposure model. Combination index (CI) analysis revealed composition-and effect-level-dependent interactions. Ternary mixtures exhibited distinct composition-dependent CI-Fa trajectories, with some compositions trending toward additivity at higher effect levels, whereas TPHP-rich mixtures showed progressively stronger synergism. Binary mixtures showed pair-dependent interactions, with TPHP-TDCIPP and TNBP-TDCIPP exhibiting contrasting interaction modes. At total nominal molar concentrations of 0.1, 1, and 10 mu M for the 1:1:1 ternary mixture, co-exposure modestly increased HaCaT monolayer permeability, reaching statistical significance at 10 mu M, and altered differentiation-related gene expression, revealing barrier-associated effects.
Untargeted metabolomics of individual and mixture exposures further revealed distinct lipid remodeling patterns, including interaction associated differences in glycerophospholipid responses. Collectively, OPE mixture hazards depend not only on individual toxicity but also on the capacity of specific components to modify combined effects, supporting improved mixture hazard characterization and prioritization of interaction-modifying contaminants.
https://doi.org/10.1016/j.jhazmat.2026.143996

****

Ceballos, D. M., Jia, C., Webster, T. F., White, R. F.
Addressing neurological health outcomes from low exposure to volatile organic compound mixtures in workplaces : progress and future directions.
Ann Work Expo Health, 2026, Vol. 70 (3), wxag026.

Numerous workplaces handle solvent-based products, exposing workers to complex and changing mixtures of volatile organic compounds (VOCs), many of which are neurotoxic.
In this commentary, we highlight key findings from research on VOC exposures in the workplace and their consequences for the central nervous system (CNS). We also provide a case study of nail salons as exposure sites. A few nail salon studies have suggested adverse health effects at low-level complex mixture VOC exposures, including significant neurological symptoms such as headaches, dizziness, difficulty concentrating, and memory loss, even when VOC exposures are below occupational exposure limits. Limited evidence specific to the health effects on nail salon workers relies on self-reported health outcomes or broad tests of mental abilities, using self-reported exposure surrogates that can lead to exposure misclassification.
Unfortunately, assessing risk one chemical at a time with its respective threshold limit-or even using the traditional industrial hygiene mixtures approach-has not been sufficient to identify key VOCs or groups of VOCs most strongly linked to CNS health outcomes in nail salon workers. Scientific methodology used to understand low-level VOC mixture health effects in this population must evolve to measure chemical mixtures more easily and accurately, employ sensitive and culturally appropriate methods to assess neurological health effects, use advanced statistical methods, and develop strategies to prevent these debilitating health outcomes. Research evaluating possible health consequences at low exposure levels is still critical for guaranteeing the health of workers exposed to VOC, even with ongoing safer alternative substitution efforts.
https://doi.org/10.1093/annweh/wxag026

****

Ierardi, A., Thompson, R., Fisher, S., Anderson, K., Grassman, J., Pavilonis, B.
Estimation of Excess Inhalation Non-Cancer and Cancer Risk From Volatile Organic Compound Mixtures in New York City Nail Salons.
Risk Analysis, 2026, Vol. 46 (11), e70391.

Nail salon workers are acutely and chronically exposed to mixtures of volatile organic compounds (VOCs), yet health risks in New York City (NYC) salons have not been systematically assessed. We performed an occupational risk assessment using integrated real-time total VOC (TVOC) monitoring and chemical-specific sampling of 11

VOCs across five NYC salons.
Median and peak exposures and their 95th percentile (upper-bound) values were used in non-cancer and cancer risk models using deterministic and probabilistic approaches. Deterministic non-cancer risk modeling indicated hazard indices (HIs) were generally below the benchmark value of 1, with exceedances observed only using upper-bound exposures in the salon with the highest VOC concentrations. The probabilistic non-cancer assessment showed a similar pattern, with some salons having non-negligible probabilities of HI exceedance despite median HIs below 1.
Deterministic and probabilistic benzene cancer risk assessments indicated exceedances of the Environmental Protection Agency (EPA) de minimis benchmark under multiple exposure scenarios. Although VOC concentrations were below occupational exposure limits (OELs), incorporating exposure variability and uncertainty identified elevated non-cancer and cancer risks under certain scenarios. Previous research has linked nail salon work to adverse health effects, including respiratory symptoms and developmental and reproductive effects, suggesting that current OELs may not adequately protect this workforce.
Our results highlight the need for improved exposure limits, chemical mixture risk assessment methods, and health protections for nail salon workers.
https://doi.org/10.1111/risa.70391

****