Interim roadmap focused on exposome research in Europe

IHEN Consortium

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Abbreviations

ADR	Adverse Drug Reactions
AI	Artificial Intelligence
ANSES	The French Agency for Food, Environmental and Occupational Health & Safety
AOP	Adverse Outcome Pathways
API	Application Programming Interfaces
AUTH	Aristotle University of Thessaloniki
BBMRI	Biobanking and Biomolecular Resources Research Infrastructure
BPS	Bisphenol S
CLP	Classification, Labelling and Packaging
COVID-19	Coronavirus disease 2019
CSS	Chemical Strategy for Sustainability
CUT	Cyprus University of Technology
CYP450	Cytochrome P450
DCAT	Data Catalogue Vocabulary
EBV	Essential Biodiversity Variables
EC	European Commission
ECHA	European Chemicals Agency
EEA	European Environment Agency
EFSA	European Food Safety Authority
EHDS	European Health Data Space
EHEN	European Human Exposome Network
EHR	Electronic Health Record
EIRENE	Research Infrastructure for EnvIRonmental Exposure assessmeNt in Europe
ELIXIR	European Life-science Infrastructure for Biological Information
EMBL	European Molecular Biology Laboratory
EMF	Electromagnetic fields
ENVI	The Environment, Public health and Food Safety committee
EOSC	European Open Science Cloud
EPHOR	Exposome project for health and occupational research
ESFRI	The European Strategic Forum for Research Infrastructures
ESPR	Ecodesign for Sustainable Products Regulation
EU	European Union
EV	Electric Vehicle
ExWAS	Exposome-Wide Association Studies
FAIR	Findable, Accessible, Interoperable and Reusable
FP7	Seventh Framework Programme
GDPR	General Data Protection Regulation
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GPS	Global Positioning System
HBM	Human Biomonitoring
HBM4EU	Human biomonitoring for Europe
HEAL	Health and Environment Alliance
HEDIMED	Human Exposomic Determinants of Immune Mediated Diseases
HERA	Health and Environment Response Agency
HIC	High Income Country
HRMS	High-Resolution Mass Spectrometry
HTA	Health Technology Assessment

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IARC	International Agency for Research on Cancer
ICL	Imperial College London
IHEN	International Human Exposome Network
INSERM	French National Institute of Health & Medical Research
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCHEM	Information Platform for Chemical Monitoring
ISEE	International Society of Environmental Epidemiology
ISES	International Society of Exposure Science
ISG	Barcelona Institute for Global Health
ITF	International Transport Forum
ITHIM	Integrated Transport and Health Impact Model
ITRE	Industry Research and Energy committee
JHU	John Hopkins University
LCA	Life Cycle Assessment
LMIC	Low and Medium-Income Countries
MG	Million Genomes
MRA	Mixture Risk Assessment
MS	Mass Spectrometry
MU	Masaryk University
NAM	New Approach Methodologies
NCD	Non-Communicable Diseases
NEXUS	Network for EXposomics in the United States
NGO	Non-Governmental Organization
NHRI	National Health Research Institutes
NIAS	Non-Intentionally Added Substances
NIEHS	National Institute of Environmental Health Sciences
NIMR	Nigerian Institute of Medical Research
NO2	Nitrogen Dioxide
OECD	Organisation for Economic Co-operation and Development
PARC	Partnership for the Assessment of Risks from Chemicals
PFAS	Per- and polyfluoroalkyl substances
PM	Particulate Matter
QTL	Quantitative Trait Loci
RACEMiC	Risk Assessment of Combined Exposure to Multiple Chemicals
REACH	Registration, Evaluation, Authorisation, and Restriction of Chemicals
RES	Renewable Energy Sources
RIVM	National Institute for Public Health and the Environment
SDG	Sustainable Development Goal
SEP	Socio-Economic Position
SSbD	Safe and Sustainable by Design
SUMP	Sustainable Urban Mobility Plan
TRAN	The Transport and Tourism Committee
UK	United Kingdom
UMC	University Medical Center
UMCG	University Medical Center Groningen
UNEP	United Nations Environment Programme
US	United States
USA	United States of America
USC	University of Southern California
USP	University of São Paulo
UP	University of Porto
UU	Utrecht University
UV	Ultraviolet

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VITO	Flemish Institute for Technological Research
VOC	Volatile Organic Compound
WHO	World Health Organization

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Executive summary

The exposome concept, introduced by Christopher Wild in 2005, refers to the totality of environmental exposures experienced over a lifetime. It was a call to better understand the non-genetic drivers of disease, which account for over 80% of the burden of non-communicable diseases and therefore represent major opportunities for improving population health, reducing inequalities, and strengthening health system sustainability.

Since its inception, numerous programmes and studies have advanced the development and integration of the exposome into the broader health research paradigm. These early efforts have demonstrated the value of the exposome approach across diverse domains, including child health, climate, chemical safety, occupational health (career), citizen empowerment, clinical practice, and urban health (cities). We are now entering a scale-up stage in exposome research where tools and insights from exposomics are expected to be translated into large and sustainable actionable frameworks that help societies tackle key health and environmental challenges, from health promotion and disease prevention to improved clinical care. At the same time, accelerating global changes—including climate change, biodiversity loss, and pollution—are reshaping exposure patterns, increasing the urgency to move from fragmented approaches towards integrated, life-course strategies. This new phase requires a clear roadmap for exposome research, detailing both the research as well as the programme needs.

IHEN partners worked together and spoke with stakeholders to develop this interim roadmap for research, innovation (including social innovation) and competitiveness. We identified five major goals. Goal 1 and 2 address the fields that are constantly shaping the complexity of the exposome (fig.2). Goal 3 and 4 address how engaging with the exposome will allow us to transform how we study and advance population health, moving from the biomedical model to an exposome model that integrates environmental and social factors into precision medicine and policy. Finally, we strongly advocate the need to support and maintain exposome infrastructures (Goal 5).

G1. To understand and anticipate how global changes modify the exposome. The major impact of global change, including climate change, biodiversity loss, and global pollution, is its ability to alter key components of the exposome and thereby influence human health directly or indirectly. While the full causal pathways between global change and the exposome are not yet fully understood, this connection is increasingly evident and urgently requires further investigation. In particular, the combined effects of different aspects of global change and various components of the exposome remain unclear and call for the development of new methodologies to assess these interactions. In parallel, the role of social inequalities, major determinants of both exposure and health vulnerability, must be a central focus. A deeper understanding of these links is essential to better anticipate future challenges and to guide more effective and equitable public health strategies.

G2 How do transitions affect the exposome. Because of the drastic effects of global changes, transitions are underway in a variety of sectors such as the energy, mobility, food, work, urban, circular economy sectors, and globally with the green transitions. The actual impacts of these societal and economic changes on the exposome and consequently on health are still unclear. The question here is the balance between delaying adaptation to such transitions and accelerating them. This goal calls for better characterization of both intended and unintended consequences, including emerging risks such as novel chemical exposures linked to circular economy practices. Understanding these dynamics is essential to ensure that transitions lead to health-positive outcomes.

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G3 How can the exposome support public health policy and regulation. As the exposome field matures, its integration into public health policy becomes increasingly important. Traditional frameworks—such as burden of disease models and health economic assessments—must be revisited considering the exposome's multifactorial, cumulative, and life-course perspective on exposure and health. Research is also needed to guide how policies in sectors like urban planning, housing, and workplace design can incorporate emerging exposome insights. Similarly, chemical and physical exposure regulations, as well as public health recommendations and risk communication, should reflect a more comprehensive and nuanced understanding of health determinants—balancing both beneficial and harmful exposures. This represents a significant shift for public health practice and will require a reorientation of priorities within health safety agencies and policy agendas.

G4 How can the exposome improve medicine. Exposome research is increasingly demonstrating its relevance for patient care and public health. The next challenge lies in scaling up its application and embedding its use into routine prevention, clinical practice, and decision-making. This includes developing more tailored and effective health interventions for specific sub-populations, supported by advances in technologies such as sensors, advanced analytical platforms, imaging, and data science. In therapeutic settings, exposomics can improve drug safety and effectiveness by identifying environmental factors that influence variability in treatment susceptibility and response, in combination with gene factors. More broadly, exposome-informed approaches are expected to advance our understanding of disease onset and progression across a wide range of medical fields. To support this integration, education on exposome science should become a core component of training for healthcare and public health professionals.

G5 Development of methods, tools, infrastructures. Analytical platforms—such as sensors, mass spectrometry, and other advanced technologies—must be further enhanced to improve the granularity, reliability, and applicability of exposure data, especially across diverse populations and real-world settings. Equally important is the development of robust, interoperable data infrastructures. A FAIR-compliant exposome data ecosystem should link electronic health records, cohort data, and other relevant sources to support secure data integration, advanced analytics, and actionable insights. Strengthening causal inference also remains a priority, calling for the advancement of toxicological research through next-generation new approach methodologies (NAMs) and AI-powered tools for data mining and toxicity prediction. This vision will require strong transdisciplinary collaboration, sustained capacity building, and institutional support to fully embed the exposome paradigm into health policy and decision-making. Targeted collaboration with the private sector—spanning pharma, MedTech, environmental monitoring, and digital health—will enable exposome insights to be embedded directly into products, services, and decision-support systems, creating competitive European offerings with international reach.

The proposed agenda aligns with the Sustainable Development Goals (SDGs), the European Green Deal, and the Competitiveness Compass, and is fully embedded within key EU policy frameworks. It supports strategic domains including cities (e.g. European Strategy for Housing and Construction, Sustainable Transport Investment Plan, European Climate Adaptation Plan, New European Bauhaus), chemicals (e.g. REACH Regulation, Chemicals Strategy for Sustainability, Clean Industrial Deal), climate (e.g. 2040 European Climate Law, European Climate Adaptation Plan, One Health Strategy), child health (e.g. European Child Guarantee, WHO Child and Adolescent Health Strategy), and clinical practice (e.g. EU Mental Health Plan, Health Promotion and Disease Prevention Initiative, EU Mission on Cancer). By generating actionable knowledge on environmental and lifestyle determinants of health, the exposome agenda helps translate research into more effective regulatory decisions, fosters clean innovation, and empowers European citizens to benefit from healthier living environments. The roadmap highlights a set of cross-cutting priorities to ensure impact. These include the need to move from fragmented to integrated approaches to health and exposure, to embed exposome science into EU policy and regulatory frameworks, to ensure that major societal transitions are health-positive and equitable, and to strengthen data infrastructures, capacity building, and citizen

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engagement. Together, these priorities provide a clear pathway for translating exposome research into tangible benefits for public health, sustainability, and innovation.

To fully realize this vision, Europe should establish a long-term European Human Exposome Initiative, bringing together research, infrastructure, policy, private sector and innovation efforts under a coordinated framework. This includes the development of large-scale, population-based exposome cohorts, sustained investment in interoperable data systems, integration with European infrastructures (e.g. EHDS, EOSC, ESFRI), and strengthened science–policy interfaces to accelerate the translation of exposome research into public health, environmental regulation, and clinical practice.

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Communication summary

The exposome—the totality of environmental exposures we experience throughout our lives—is a powerful concept for understanding what drives health and disease beyond genetics. With its large impact on health, the exposome offers unprecedented opportunities to improve population health. As exposome science has matured over the last two decades, it is now time to implement it into preventive and curative care, and to translate its insights into practical solutions for health promotion, disease prevention, and clinical care.

This roadmap, developed by IHEN and its partners, outlines five urgent goals. First, we must understand how global changes—climate change, pollution, biodiversity loss—are altering our exposures and health risks (Goal 1). Second, we need to evaluate how major societal shifts like the energy transition and circular economy influence the exposome and identify potential unintended consequences (Goal 2).

Third, the exposome must be embedded in public health policy. This includes rethinking traditional models to reflect cumulative, life-course exposures and informing policies in urban planning, chemicals regulation, and workplace safety (Goal 3). Fourth, exposome insights can improve medicine by enabling more tailored prevention and treatment strategies. Achieving this requires integration into clinical practice and health training (Goal 4).

Finally, further development, harmonisation, and implementation of tools—such as sensors, high-resolution data platforms, and AI-driven analytics—are essential to support wide-scale use. Central to this is the creation of FAIR (findable, accessible, interoperable, and reusable) data ecosystems that integrate environmental, social-determinants, health, and administrative data while enabling secure linkages, advanced analysis, and real-world applications across diverse populations and settings (Goal 5).

This agenda aligns with key EU priorities, including the European Green Deal, REACH Regulation, the New European Bauhaus, the EU Mission on Cancer, and child and climate health strategies. By advancing exposome science, Europe can better anticipate health risks, design smarter regulations and healthier environments, foster innovation, and empower citizens to thrive.

The roadmap also highlights key cross-cutting priorities for action. These include moving from fragmented to integrated approaches to health and exposure, embedding exposome science into policy and regulation, ensuring that societal transitions are health-positive and equitable, and strengthening data infrastructures, capacity building, and citizen engagement.

To fully realize this vision, Europe should establish a long-term European Human Exposome Initiative, bringing together research, infrastructure, policy efforts and private sector investment under a coordinated framework.

We invite policymakers, scientists, industry partners and citizens to join in realizing this vision for a more resilient, equitable, and health-informed future.

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Scientific context

Human health is shaped by the dynamic interplay between genetics and the environment. While the human genome has been mapped in detail, the environmental (or non-genetic) drivers of health and disease remain less well understood—despite contributing to more than 80% of the global burden of non-communicable diseases. To address this gap, the concept of the *exposome* was introduced by Dr. Christopher Wild in 2005. He defined it as the totality of environmental exposures—from the prenatal period onwards—that influence human biology and health throughout the life course.

Since then, exposome science has matured into a vibrant interdisciplinary field known as *exposomics*, which integrates environmental, behavioural, biological, and social data to comprehensively assess how non-genetic factors shape health over time. Rather than isolating individual risk factors, exposomics recognises that exposures occur in complex mixtures, accumulate over a lifetime, and act within specific socio-biological contexts. This approach allows for a more accurate and equitable understanding of what causes disease and long-term health.

Over the past decade, major international and European research programmes have advanced exposome science and generated promising insights across key domains, including child health, climate, chemical safety, occupational health, citizen empowerment, clinical practice, and urban health. With tools, technologies, and foundational knowledge in place, the next step within the exposome field is to translate exposomics into practical solutions for public health and medicine. This requires scaling-up current efforts and embedding exposome insights into prevention strategies, clinical care, and policy frameworks.

The *International Human Exposome Network (IHEN)* was established to connect and align European research initiatives in exposomics and to accelerate this transition from research to real-world impact. IHEN aims to build a coherent, interdisciplinary community that fosters collaboration, shares resources, and defines strategic directions for exposome science across Europe. A core objective of IHEN is to develop and promote a unified vision for how exposome research can support healthier societies, informing policy and innovation. This *roadmap* is a key expression of that mission. It identifies five strategic goals and priority areas for action—co-developed with stakeholders from academia, public health, policy, and civil society—to ensure that exposome science delivers on its full potential and becomes a transformative force for health in Europe and beyond.

Exposome: The integrated compilation of all the physical, chemical, biological and psychosocial exposure factors, and their interactions, which have an impact on biology and health.

Exposomics (definition to a science audience): A transdisciplinary field aimed at a comprehensive and discovery-based understanding of how the exposome influences biology and health.

Exposomics (extended definition for IHEN): A field that studies the compilation of all physical, chemical, biological, and psychosocial factors that impact biological systems by integrating data from a variety of interdisciplinary methodologies and streams, to enable discovery-based analysis of environmental influences on human health.

Exposomics (preliminary definition for public communication). Short: The comprehensive study of the effects of environmental factors on health. **Extended:** A scientific field that attempts to discover previously unknown ways in which the environment affects human health by gathering and analysing large amounts of data from many different sources, such as the air, food, chemicals, and blood and using a variety of methodologies.

Definition of the exposome and exposomics adopted by the IHEN consortium

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Introduction

This interim roadmap, developed by the International Human Exposome Network (IHEN), sets out a structured agenda for advancing exposome research across Europe. It is intended as a strategic guide for the European Commission, EU agencies, research funders, national authorities, public health institutes, and other key stakeholders engaged in environment and health policy, regulation, and research.

Purpose

The roadmap aims to shape future research priorities, support policy development, and foster dialogue among the diverse actors working in exposome science. It provides a shared framework to identify knowledge gaps, emerging research areas, and critical policy needs. This interim version will serve as the foundation for wider consultations—through surveys, workshops, and policy dialogues—that will inform a final European exposome research agenda.

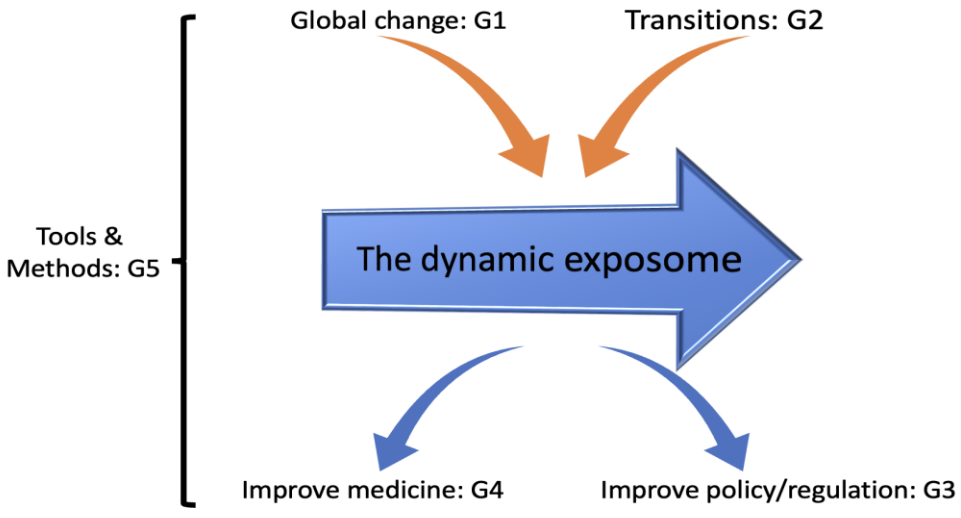
Overview of goals

The roadmap is structured around five strategic goals, grouped into three thematic categories:

1. **Global Change and Societal Transitions (Goals 1 & 2):**
   Understand how global forces—such as climate change, biodiversity loss, and major transitions in energy, food, and urban systems—are reshaping the exposome and health risks

2. **Translation into Policy and Practice (Goals 3 & 4):**
   Investigate how exposome insights can inform regulation, enhance public health strategies, and transform clinical medicine through better prevention and tailored care

3. **Tools, Technologies, and Infrastructure (Goal 5):**
   Advance and scale analytical, data, and digital solutions needed to make exposome research operational, inclusive, and impactful.



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Structure

Each goal consists of several related subgoals, e.g. Goal 1.1, 1.2. For each subgoal, we outline the objective, relevance, research needs (knowledge gaps and expected impact), and policy relevance (e.g. alignment with EU Green Deal, SDGs, Mission Cancer).

This document is a first step toward a coordinated and impactful European exposome strategy. Each goal is led by an IHEN partner institution who will further develop content in collaboration with stakeholders.

Methodology

The International Human Exposome Network (IHEN) project is led by 12 leading institutions across Europe engaged in exposome research. The project established IHEN, a global network of scientists, policymakers, local authorities, industry representatives, and civil society organisations. To develop this roadmap, IHEN partners designed a structured methodology to engage both the scientific community and relevant stakeholders in identifying current knowledge gaps, research priorities, and policy needs.

While this document presents an interim agenda, it represents the first step toward a comprehensive and fully co-created European exposome roadmap. The process for this interim version has been intentionally focused to enable timely input and reflection, and it will be expanded through broader consultations—including targeted surveys, workshops, and policy dialogues—leading to the final roadmap.

In this first iteration, IHEN partners identified five overarching goals that reflect the pressing research challenges and opportunities at the intersection of the exposome and public health. These span from planetary-level dynamics (e.g. global change) to regional and individual-level priorities, such as regulatory application, clinical relevance, and technology development. Sub-goals within each category were established through internal expert consultations and initial stakeholder engagement.

To guide prioritisation, we applied criteria such as scientific novelty, relevance to population and planetary health, potential for innovation, and likely policy impact. In parallel, a policy needs assessment was conducted. This involved systematic mapping of European and national policy frameworks, followed by a stakeholder survey to identify gaps at the environment–health–climate nexus.

By comparing research needs from both scientific and policy perspectives (see figure below), IHEN identified priority areas that merit focused investment and further development. This interim roadmap sets out those priorities and serves as a foundation for expanded engagement and refinement. It will be used to guide the development of the final European exposome research agenda.

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G1 To understand and anticipate how global changes modify the exposome

Climate change, biodiversity loss, evolving pollution patterns, and social inequalities are key drivers that modify the nature, intensity, and distribution of exposures across populations and over the life course. However, their combined and interacting effects remain insufficiently understood. G1 aims to address these gaps by examining how these global changes alter the exposome through four complementary dimensions: climate-related exposures, biodiversity degradation, emerging pollution profiles, and socially structured inequalities in exposure and vulnerability. This integrated approach will enable a more comprehensive understanding of exposure-health relationships and support the development of effective and equitable public health strategies.

G1.1 Impact of climate change on the exposome

Objective

The objective is to provide a structured approach to conceptualising the diverse links between two broad, complex topics — climate change and the human exposome — by identifying specific research gaps that should be prioritized to advance understanding of the interrelationships between these topics, but that could not be adequately addressed through a research focus on either topic individually.

Relevance

Both climate change and the exposome are recognised health research priorities for Europe, but efforts to align and integrate these research priorities are in relatively early stages. Integration of these topics is relevant in several ways: i) integration of the exposome approach in quantifying the health impacts of climate change; ii) understanding how efforts to adapt to and iii) mitigate climate change will shape the exposome and its influence on health.

Previous efforts have conceptualised the linkages between climate change and exposome research. This has largely focused on how integration of additional exposures using an exposome approach can yield better understanding of the health impacts of climate change (1,2). Integration of the exposome into climate and health research is much less developed in the context of adapting to climate change by reducing exposure or vulnerability to climate hazards or efforts to mitigate climate change by reducing emissions of greenhouse gases and increasing carbon sinks.

Building on existing frameworks to characterize the intersection of health and climate change (3), we identify research gaps that could be addressed by incorporating the exposome approach into research on the health impacts of climate related exposures, adaptation, and climate change mitigation.

Research needs

Health impacts

Climate hazards including heat, drought, floods, and storms can have diverse impacts on nearly all exposome domains. However, many of these pathways are complex and indirect, and their links to infectious diseases, non-communicable diseases, and mental health are not well characterized.

Increasing temperature is already a major threat to health, with summer temperatures in Europe resulting in 61,000 and 47,000 excess heat-related deaths in 2022 and 2023, alone (4). Temperatures in Europe are warming at twice the rate of the global average (3), with warming particularly rapid in the Arctic and Nordic regions of Europe. Climate change is contributing to increased levels of ground-level ozone, risk of wildfires, floods, and in some, but not all regions, allergenic pollen (3). Rising temperatures contribute to increased pesticide use in agriculture and the release of long-stored contaminants like mercury and persistent organic

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pollutants from melting glaciers and permafrost. Changing precipitation patterns intensify agricultural runoff, leaching pollutants into freshwater systems, while rising sea levels contribute to greater coastal contamination. Additionally, warming oceans promote bioaccumulation of pollutants such as methylmercury and microplastics in seafood, increasing dietary exposure risks. Frequency of droughts and heat wave days has been linked to increases in food insecurity. Climate change can also impact the climate suitability for a number of infectious diseases in Europe including coastal pathogens (Vibrio spp), zoonotic pathogens (e.g. West Nile Virus, and leishmaniasis), arboviral disease (e.g. dengue, chikungunya, and Zika), and ticks (3).

The body of evidence documenting health impacts of climate related exposures in Europe is rapidly increasing. While emerging evidence has considered the joint effects of temperature and air pollution, most studies have examined hazards in isolation, presenting an opportunity to generate new insights from the incorporation of the exposome. Priority research lines:

- Climate change is amplifying the frequency and intensity of multiple, interacting hazards. However, the effect on health, particularly on internal exposome markers (e.g. omics, biomarkers), of co-occurring exposures, and their cumulative impacts over the life course are largely unknown.
- Climate change is altering exposure to climate-sensitive air pollutants including ozone and wildfire smoke. These often occur together alongside extreme heat. However, the synergistic health effects of multiple, interacting climate-related exposures within the physio-chemical exposome is not well characterized.
- Warmer temperatures and changes in precipitation are expanding the geographic range suitable to the transmission of vector-borne-diseases such as dengue, chikungunya, and Zika. How infection risk interacts with other dimensions of the exposome (e.g. physio-chemical, built environment, and social) is not known.
- Increasing temperatures can affect health behaviours including mobility patterns, comfort of active transport, and amount of leisure-time physical activity. This can subsequently affect multiple exposures (e.g. air pollution, transport noise, and green space) and diverse mental and physical health outcomes.

Adaptation

Very little knowledge is available regarding how climate change adaptation can lead to healthier (or more hazardous) exposome profiles. Priority research lines:

- Adaptation actions, such as increasing tree cover and other vegetation to enhance passive cooling, can have diverse impacts on exposure to green space, pollen, and risks of vector borne disease and vegetation fire smoke. Similarly, replacing impermeable surfaces with permeable green space as part of flood and heat adaptation can affect exposure to green space and chemical contamination of surface water via run-off. Comprehensive evaluation of the potential synergies and trade-offs for health of nature-based solutions for adaptation using an exposome approach are needed.
- Shifting work schedules to hours outside of the warmest periods is an important adaptation strategy to protect outdoor workers from heat stress. However, the implications of such shifts on health behaviours and the social exposome (e.g. social cohesion) are not well understood.

Mitigation

While there is a movement towards considering multiple exposures in scenario modelling studies of health impacts under different climate policies, this work has not explicitly applied an exposome approach. Priority research lines:

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- How do specific climate policies simultaneously influence multiple exposures, through the main pathways that lead to health co-benefits (e.g. air pollution from fossil fuel combustion, brake and tyre wear particles from electric vehicles, exposure to greenspace)?
- What are the implications of energy efficient buildings on indoor environmental exposures (e.g. air pollution, thermal comfort)?
- What methodological approaches (e.g. Agent Based Modelling, microsimulation) are best suited to consider the health impacts of multiple exposure pathways affected by climate policy in an integrated way?

Expected impact and policy relevance

Supporting the European Green Deal, including the European Climate Law and Fit for 55

Research on this topic would support the broad set of policy initiatives included in the European Green Deal, including those that set the EU on the path to climate neutrality by 2050 and the intermediate target of a 55% of net GHG emissions compared to 1990 by 2030. It also supports the EU strategy on adaptation to climate change, the biodiversity strategy for 2030; and the Zero Pollution Action Plan.

Supporting climate change adaptation.

Research on this topic could also support health-centred climate change adaptation through the EU Mission on Adaptation to Climate change, which aims to support regions and local authorities to improve climate resilience.

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G1.2 Impact of biodiversity loss on the exposome

Objective

The aim is to investigate and explain the multifaceted impacts of biodiversity loss on the human exposome and identify and quantify the ways through which biodiversity degradation alters human exposures, both directly and indirectly.

Relevance

Biodiversity encompasses the complex variety of life at all scales, ranging from genes to species to ecosystems. It is foundational to all ecosystem services, which sustain human health and well-being and

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ultimately the survival of our species (1). Biodiversity and functional ecosystems play a critical role in regulating air and water quality, soil fertility, pollination, climate stability, and disease control. Major contemporary threats to biodiversity include natural resource overexploitation, climate change, environmental pollution, and anthropogenic conversion of natural habitats to agricultural or urban ecosystems.

In this context, biodiversity loss refers to net declines in species richness, functional diversity, genetic diversity, and ecosystem integrity across spatial and temporal scales. While recognising that local restoration initiatives may enhance biodiversity in specific settings even though broader regional and global trends continue to show overall decline.

The current crisis-level losses of biodiversity disrupt ecosystem services, which negatively affects air and water quality, food security, disease dynamics, and psychosocial well-being and increases exposure to allergens and pathogens. For example, the loss of predators and competitors can facilitate the spread of vector-borne diseases, such as Lyme disease, malaria, and dengue fever. While urbanisation and disruption of natural habitats create expanding hazardous interfaces between people, livestock, and wildlife reservoirs of zoonotic disease. Recent studies suggest that the escalated emergence of various infectious pathogens, including COVID-19, can be attributed to biodiversity loss (2). These dynamics are particularly relevant in contexts of deforestation, extractive industries, land-use change, and intensified human-wildlife contact, including in low- and middle-income countries. Furthermore, biodiversity loss can exacerbate the impacts of climate change, compounding exposure risks.

The Biodiversity Hypothesis states that early life exposure to biodiverse microorganisms is central for immune system functioning (3), possibly as microbial diversity impacts the gut microbiome (4). On the contrary, the loss of biodiversity leads to immuno-deregulation and chronic inflammation with a consequent increase in chronic and autoimmune diseases, including asthma and allergic diseases (5), but also mental illness. In addition, biodiversity plays a critical role in regulating environmental pollutants. For example, wetlands with rich biodiversity can filter out heavy metals and other pollutants from water sources (6). Loss of such ecosystems can result in higher levels of contaminants in human environments, increasing the risk of exposure to toxic substances.

Research needs

Despite growing awareness of the health implications of biodiversity loss, significant gaps remain in our understanding of the specific mechanisms and exposure pathways involved. Addressing these gaps requires targeted research in the following areas:

Mechanistic studies on exposure pathways

- There is a need for detailed investigations into how biodiversity loss alters pathogen reservoirs and vectors, influencing the emergence and transmission of zoonotic diseases (7). This includes studying changes in host-pathogen dynamics, vector ecology, and the dilution effect in various ecosystems. For example, predator loss can raise Lyme disease risk via more rodent hosts, reduced vertebrate diversity can boost mosquito-borne transmission, and overall biodiversity loss may favor infectious disease re-emergence. Particular attention should be given to African contexts, where deforestation, land-use change, and bushmeat hunting increase human–wildlife contact and elevate the risk of zoonotic pathogen spillover. Studying these dynamics will be critical to advancing a planetary health understanding of biodiversity–exposome interactions.

- There is a need for research on how reduced biodiversity affects the bioaccumulation and biomagnification of environmental pollutants in food webs, leading to altered human exposure to harmful chemicals such as heavy metals, persistent organic pollutants, and endocrine disruptors. Research should also explicitly address increases in harmful algal blooms linked to ecosystem

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imbalance, as these represent distinct exposure pathways with neurological, hepatic, and immune implications. In addition, research should investigate how extractive industries, deforestation, and land-use change alter ecosystem health metrics (e.g. forest cover loss, soil degradation, water contamination) and increase both chemical exposures (e.g. heavy metals, particulate matter, agrochemicals) and human–wildlife contact in rural populations. Particular attention should be given to how these combined pressures influence immune-related components of the exposome, including inflammatory, infectious, and autoimmune pathways.

- There is a need for studies on how biodiversity loss impacts the human microbiome through changes in environmental microbial diversity. This includes examining the effects on gut, skin, and respiratory microbiota, and the subsequent implications for immune function and disease susceptibility. Equally, a better understanding of causal links between biodiversity exposure and human health, including mental health, is required. These pathways should be considered alongside other established determinants of microbiome composition and immune regulation, including nutrition, social interactions, and broader socio-environmental conditions.
- There is a need to understand how biodiversity loss, including declines in soil biodiversity and agricultural intensification, may alter food diversity, micronutrient composition, and contaminant profiles, with downstream consequences for the human gut microbiome, nutritional balance, and long-term health.

Quantification of biodiversity-exposome relationships

- There is a need to develop databases and standardized metrics to quantify the relationship between biodiversity levels and specific exposome components. This involves integrating ecological indicators, including the essential biodiversity variables (EBVs, a standardized set of measurements monitoring biodiversity loss), with human exposure data to create comprehensive models. Biodiversity quantification should rely on measurable indicators (e.g. species richness indices, Shannon or Simpson diversity metrics, functional trait diversity, genetic diversity proxies), which can inform biodiversity-related exposure assessments. Clear differentiation between highly modified ecosystems, semi-natural systems, and relatively intact ecosystems will allow more precise exposure contrasts.

  There is a need for high-resolution spatial and temporal studies to map biodiversity loss, both below and above ground and to correlate it with changes in exposure patterns across different populations and regions. This includes the use of remote sensing, geographic information systems (GIS), real-world data sources, digital tools, and longitudinal cohort studies.

Integration of multidisciplinary data

- There is a need to combine data from ecology, epidemiology, toxicology, and environmental sciences - and, where possible, human physiological, biological, and genetic parameters - to build holistic models of how biodiversity loss affects the exposome. This requires interdisciplinary collaboration across natural sciences, biomedical sciences, and social sciences, as well as the development of interoperable databases and advanced analytical tools for multi-omics integration.
- There is a need to apply ExWAS methodologies to identify associations between biodiversity-related exposures and health outcomes. This includes using high-throughput technologies and bioinformatics to analyse complex exposure mixtures (see Goal 5).

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- There is a need to use systems-based approaches to investigate bidirectional feedback mechanisms between biodiversity loss and the human exposome, including how anthropogenic exposures (e.g. chemical pollution, land-use pressures, resource extraction) contribute to ecosystem degradation and further biodiversity decline.

Vulnerability and equity assessments

- There is a need to investigate how biodiversity loss disproportionately affects vulnerable populations, including those in low-income communities, indigenous groups, and regions heavily dependent on ecosystem.
- There is a need for research on factors that influence the resilience of human populations to biodiversity-related exposures, including socio-economic, cultural, and policy dimensions as well as impacts on traditional medicine systems that depend on biodiversity as a primary healthcare resource in many regions.

Impact of biodiversity loss on specific diseases

- There is a need for research on the impact of biodiversity loss on allergies and auto-immune diseases. For example, comparing the immune health of children going to schools in highly built-up vs semi-natural or natural environments and the impact on their internal microbiome diversity.
- There is a need to investigate the association of mental health with environments displaying high or poor biodiversity and its correlation with internal microbiome diversity, including emerging concepts such as solastalgia, biodiversity-related distress, and behavioural adaptations.

Methodological innovations

- There is a need to develop innovative biomonitoring tools to detect and quantify exposures linked to biodiversity loss, such as biomarkers of ecosystem-derived pollutants or microbial diversity indicators. They should include susceptibility, exposure, and effect biomarkers (e.g. genetic, epigenetic, immune, and inflammatory markers), and integrate real-world data and digital tools.
- There is a need to create predictive models to forecast future exposome changes under different biodiversity loss scenarios, incorporating climate change projections and land-use changes, and to identify populations and communities at highest risk.

Expected impact and policy relevance

Contribution to the European Green Deal

The European Green Deal aims to make Europe climate-neutral by 2050, with a strong emphasis on protecting biodiversity and promoting sustainable agriculture. Research findings can support these goals by highlighting the health co-benefits of biodiversity conservation and providing data to guide sustainable land-use planning and pollution control.

Alignment with the Sustainable Development Goals (SDGs)

This research directly supports SDG 3 (Good Health and Well-being), SDG 13 (Climate Action), and SDG 15 (Life on Land) by demonstrating the interconnectedness of the health of the planet and the health of humans.

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By explaining the health impacts of biodiversity loss, this work will help align health policies with broader sustainability goals.

Integration with the New European Bauhaus Initiative

The New European Bauhaus initiative promotes sustainable and inclusive living environments. Understanding the role of biodiversity in shaping the exposome can inform the design of urban spaces that enhance ecological integrity and reduce harmful exposures, contributing to healthier, more resilient communities.

The Convention on Biological Diversity and Aichi Targets

The research aligns with global biodiversity conservation commitments, informing strategies to achieve the Post-2020 Global Biodiversity Framework and Aichi Biodiversity Targets. Understanding exposome-related risks can help shape biodiversity action plans that also integrate public health considerations.

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services)

Findings will contribute to IPBES assessments, strengthening the scientific basis for biodiversity-health linkages and providing evidence for policy recommendations that enhance ecosystem resilience and human well-being.

Climate adaptation and mitigation strategies

As climate change accelerates biodiversity loss, this research will inform adaptation strategies that address both environmental and health challenges. It will also highlight the co-benefits of biodiversity conservation for climate mitigation and health resilience.

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G1.3 Impact of global pollution changes on the exposome

Objectives

To characterize and mitigate risks and exposures from emerging pollutants driven by global changes, including shifts in industrial practices, waste management, and pollution pathways. The focus is on understanding novel chemical exposures, their interactions with biological systems, and their long-term health effects.

Relevance

Global chemical production and use have increased rapidly and are expected to continue rising, with thousands of substances currently on the market and new compounds introduced each year. At the same time, plastic pollution—including micro- and nanoplastics—has become widespread across air, water, soil, and food systems, creating new exposure pathways. Together, these trends are increasing chemical complexity in the exposome and introducing poorly characterized substances.

Food systems are a major source of environmental contamination. Intensive agriculture relies on pesticides, fertilizers, and antibiotics, contributing to soil degradation, water pollution, antimicrobial resistance, and chemical residues in food. Marine and aquatic pollution further leads to bioaccumulation of substances such as methylmercury, PFAS, and microplastics. Emerging food sources (e.g. plant-based, algae, insects, cell-cultured products) also introduce new and insufficiently studied exposure scenarios.

Exposure patterns vary across Europe due to differences in geography, land use, and proximity to contaminated sites. Legacy pollution from industrial and mining activities continues to contribute to current exposure burdens, while regulatory changes and shifts in production and consumption further modify exposure profiles over time. These dynamics often disproportionately affect socioeconomically disadvantaged populations.

Recycling practices and consumer products introduce additional risks, as hazardous substances (e.g. flame retardants, dioxins) can re-enter supply chains through recycled materials (1). New “green” or biodegradable materials may also generate poorly understood breakdown products. Cross-border pollution and persistent contaminants such as lead further complicate exposure patterns.

The transition to sustainable technologies may introduce unintended risks. Replacement chemicals (e.g. BPS, short-chain PFAS) are often insufficiently assessed (2), and growing battery waste raises concerns about environmental contamination with metals such as lithium, cobalt, and nickel (3). Without improved regulation and waste management, these developments may create new health risks.

Exposomics provides a transformative approach to understanding these challenges by enabling large-scale, untargeted analysis of chemical exposures. High-resolution mass spectrometry (HRMS) can detect thousands of known and unknown compounds, identify biomarkers of past exposures, and capture interactions between environmental chemicals and biological responses. These advances now allow population-level studies of exposure–disease relationships across the full chemical landscape.

Research needs

To understand and address the impact of global pollution changes on the exposome, research needs to:

- To develop and scale up harmonized non-targeted and suspect screening methods for emerging pollutants across environmental and human matrices, including coordinated efforts for exposome-scale analysis and integrated database creation. This involves :
    - Advancing high-resolution mass spectrometry (HRMS) techniques for untargeted screening of chemical contaminants in air, water, soil, food, and biological samples

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  - Establishing interoperable, quality-controlled data infrastructures to support the identification, annotation, and sharing of unknown and low-abundance compounds
  - Facilitating EU-wide coordination for database development to enable cross-sector comparison, retrospective analyses, and early warning of novel chemical threats
  - Scaling up non-targeted exposure monitoring to capture real-world chemical exposures in large population studies with longitudinal follow-up (cohort studies) to build evidence on chemical exposure–disease relationships across entire populations, supported by harmonized data standards and consistent implementation of GDPR across Member States to enable secure cross-border data sharing.
  - Integrating complementary multi-analyte targeted mass spectrometry approaches to enable accurate quantification, validation, and harmonization across studies.
  - Developing hybrid targeted–non-targeted workflows to enable comprehensive assessment of known, emerging, and previously unidentified exposures.

- Geographic and environmental variability gaps: Little research integrates the effects of varying pollutant exposure across different EU regions, including urban–rural gradients, agricultural areas, coastal zones, and industrial hotspots (current and historical). Higher exposure burdens in marginalized and socioeconomically disadvantaged groups, particularly those living near industrial facilities or contaminated sites, must be systematically addressed through targeted monitoring, remediation, and equity-focused regulatory action. Citizen science approaches should be leveraged to capture fine-scale geographic variability, improve hotspot identification, and strengthen community engagement in exposome research.

- Interdisciplinary integration: There's limited integration between fields such as environmental science, genomics, metabolomics, and epidemiology. In particular better mapping across Europe of pollution hotspots for industrial contaminants such as PFAS (4) is needed.

- The health impacts of long-term exposure to contaminants in recycled materials (especially plastics and electronics) remains poorly explored.

- Research on how chemical mixtures such as microplastics, pesticides interact with the human gut microbiome, neuroendocrine, immune, dermal, and reproductive systems are still limited. Studies should focus on synergistic and cumulative impacts, especially in low-dose chronic exposures, and develop sensitive, multi-omics-based biomarkers of effect and susceptibility in humans. Coordinated research efforts are needed to link exposome data with such early biological responses, supporting better risk assessment and regulatory decision-making.

- There is a critical need to investigate the combined and cumulative effects of multiple stressors across the exposome, including chemical stressors (e.g. air pollutants, endocrine-disrupting chemicals, metals), physical stressors (e.g. noise, artificial light at night, heat, ionizing and non-ionizing radiation), and psycho-social stressors (e.g. chronic stress, socio-economic disadvantage). Particular attention should be paid to vulnerable populations such as children, pregnant women, occupationally exposed workers, and the elderly.

- While the EU promotes battery recycling under the Circular Economy Action Plan, regulations on waste management and worker protection are still catching up with the rapid increase in battery production.

- Research into bioaccumulation of rare earth elements in human tissues is limited, especially for long-term health effects.

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- Research should address indoor air pollution in African regions, focusing on chemical mixtures from solid fuel cooking and their interactions with other health risks like tuberculosis and HIV.

Expected impact and policy relevance

Advancing knowledge on emerging pollutants and global pollution dynamics will strengthen the EU's capacity to anticipate, monitor, and mitigate complex and evolving chemical exposures. This will support a shift towards more preventive, exposome-informed risk assessment approaches that better reflect real-world cumulative exposures.

The results will directly inform EU regulatory frameworks on chemicals and pollution, including REACH, the Chemicals Strategy for Sustainability, and the Zero Pollution Action Plan, by improving the identification of emerging risks, substitute chemicals, and mixture effects. They will also support food safety, water quality, and circular economy policies by addressing contamination pathways across environmental media and supply chains.

Improved exposome-scale monitoring and data integration will enhance early warning systems and regulatory preparedness, enabling faster responses to new chemical threats and supporting more harmonised approaches across Member States.

This work will also contribute to more equitable policies by identifying populations disproportionately affected by pollution, supporting targeted interventions in vulnerable communities and high-exposure regions.

At the global level, the research aligns with SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), and SDG 12 (Responsible Consumption and Production), supporting international efforts to reduce pollution and its health impacts.

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G1.4 Impact of social inequalities between and within countries

Objective

To investigate and contribute to reducing health inequalities associated with environmental exposures and global environmental change, recognising that such differences are often systematic, avoidable, and unjust.

Relevance

Substantial disparities in health outcomes persist across and within populations, with marked differences in incidence and mortality linked to variations in exposure, vulnerability, and access to care (1,2).

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These inequalities are evident both within countries and globally, particularly between high-income countries (HICs) and low- and middle-income countries (LMICs).

While social inequalities are a policy priority in their own right, they are increasingly exacerbated by climate change and environmental degradation. These interacting pressures disproportionately affect vulnerable populations, particularly in the Global South. The concept of a syndemic captures this interaction, highlighting how social disadvantage, chronic diseases (e.g. obesity, diabetes), and environmental exposures combine to amplify health risks and adverse outcomes.

Within the exposome framework, social determinants are a core component of the general external exposome, interacting with specific environmental exposures and internal biological processes. However, the integration of these domains remains a key scientific and methodological challenge.

Socio-economic position (SEP) is commonly used as a proxy for the social exposome, encompassing dimensions such as income, education, and social status. However, additional factors—including social support, networks, gender, and ethnicity—also shape exposure profiles and health outcomes. Importantly, SEP should not be treated solely as a confounding variable, but rather as a fundamental determinant that structures exposure pathways and health trajectories.

The influence of social inequalities operates across the life course. Early-life conditions, including adverse childhood experiences and socioeconomically patterned behaviours (e.g. diet, physical activity, smoking), contribute to cumulative biological changes and long-term disease risk. These processes are well described within lifecourse epidemiology, which should be systematically integrated into exposome research.

Recent conceptual advances, such as the Social Exposome framework developed in the Equal-Life project (3), provide a more comprehensive understanding of how social, environmental, and structural factors interact across scales—from individual to societal levels. These frameworks emphasise the importance of structural determinants, discrimination, and social context in shaping exposure and vulnerability.

The concept of embodiment further strengthens this perspective by describing how social conditions are biologically embedded over time. Social, economic, and cultural capital interact with environmental exposures to influence biological systems throughout the life course. This highlights the need to integrate sociological and biological approaches to better understand how social trajectories translate into health outcomes.

Finally, cross-country comparisons of the exposome require greater consideration of geopolitical and structural factors, including historical patterns of resource extraction, global trade, and power asymmetries. These dimensions are critical to understanding global disparities in environmental exposures and health risks.

Research needs

To better understand and address the impact of social inequalities on the exposome, the following research priorities are identified:

- Develop robust theoretical frameworks that integrate social, structural, and environmental dimensions of the exposome, ensuring that societal organisation, power structures, and inequalities are explicitly considered.
- Improve the definition and measurement of social determinants, including SEP, gender, ethnicity, social networks, and support systems, recognising that these dimensions are distinct and not interchangeable.
- Incorporate geopolitical, historical, and post-colonial perspectives into exposome research to better capture global inequalities and environmental injustices, particularly in LMIC contexts.

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- Advance the conceptualisation and empirical application of socio-markers as measurable indicators of social exposures, supported by methodological development and pilot studies (4).
- Strengthen analytical approaches to capture interactions across multiple layers (societal, environmental, biological), including the use of advanced causal inference methods such as mediation analysis, Bayesian networks, and counterfactual modelling.
- Investigate how historical and structural inequalities contribute to differential exposure burdens, particularly in the Global South, including the role of extractive economies and global supply chains.
- Examine the health impacts of contemporary social and digital environments, including social media, digital technologies, and AI-driven systems, on mental health and behavioural patterns.
- Assess how gender roles and social norms influence exposure pathways, including disproportionate risks from household air pollution and waterborne hazards.
- Study how migration, forced displacement, and environmental crises alter exposure profiles and health risks across populations.
- Investigate the impact of military conflicts on environmental exposures and health, including both direct and indirect pathways.

Expected impact and policy relevance

Supporting EU health equity and social policy frameworks

This research will strengthen the evidence base for reducing health inequalities within and across Europe, supporting initiatives such as the European Pillar of Social Rights, the EU Health Equity Strategy, and the European Child Guarantee. By identifying how social determinants shape exposure and vulnerability, it will inform more targeted and effective public health interventions.

Integrating equity into environmental and climate policies

Findings will support the European Green Deal, the Zero Pollution Action Plan, and the EU Climate Adaptation Strategy by embedding equity considerations into environmental and climate policies. This will help ensure that mitigation and adaptation measures reduce, rather than exacerbate, existing social and health disparities.

Advancing exposome-informed risk assessment and regulation

Incorporating social determinants into exposome research will enable more comprehensive risk assessment frameworks that account for differential exposure and vulnerability across populations. This will improve the design and implementation of chemical, environmental, and occupational health regulations.

Addressing environmental justice and vulnerable populations

The research will support policies aimed at protecting vulnerable and marginalized groups, including those disproportionately exposed due to socio-economic disadvantage, occupation, or geographic location. It will contribute to equity-focused monitoring, prevention strategies, and remediation efforts.

Aligning with global frameworks and SDGs

This work aligns with SDG 3 (Good Health and Well-being), SDG 10 (Reduced Inequalities), and SDG 13 (Climate Action), and supports international agendas on environmental justice and sustainable development. It will also contribute to global discussions on health equity in the context of environmental and planetary change.

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G2 How do transitions affect the exposome

Goal 2 focuses on understanding how major transitions in Europe reshape the human exposome. These transitions offer substantial health benefits, such as reduced pollution, increased physical activity, and healthier diets, but also introduce new or shifting exposures that may affect vulnerable populations. By adopting an exposome-based approach, G2 aims to anticipate cumulative and interacting exposures, identify risks and co-benefits, and inform strategies to ensure that Europe's transformations are not only sustainable and climate-aligned, but also safe, equitable, and health-promoting.

G2.1 Impact of energy transition

Objective

Investigate the effects of energy transition on the exposome, considering changes in environmental exposure and the potential impact on human health.

Relevance

The energy transition in the EU landscape is a wider aspect of the green transition and a key pillar of the EU Green Deal (1) —aligning economic growth with climate goals, sustainability, and zero pollution. The EU aims to achieve a decarbonized energy system by 2030 and a carbon-neutral system by 2050. Throughout the EU plans, the need for transitioning from fossil fuels to renewable energy sources (RES) is emphasized, aiming for a 42.5% share of RES by 2030 (2). In line with this, the Ecodesign for Sustainable Products Regulation (ESPR) (Regulation (EU) 2024/1781), establishes criteria for the transition to energy-efficient products, promoting sustainable practices across their entire life cycle.

The human exposome can be influenced by the energy transition, including shifts in climate, environmental pollution and chemical exposure, both in positive and negative ways. Decarbonization of energy, for instance, can eliminate air pollution and greenhouse gas (GHG) emissions, as well as improve the quality of workers' health in industrial environments.

However, the transition also introduces new and evolving exposure pathways. Emerging technologies and materials used in renewable energy systems (e.g. batteries, photovoltaics, hydrogen systems, and wind turbines) may introduce novel chemical, particulate, physical, and psychosocial exposures. For example, increased deployment of heat pumps may contribute to residential noise exposure, while the production and recycling of solar panels and batteries may generate chemical exposures.

In addition, the transition may shift environmental and health burdens geographically and socially, raising equity concerns. The extraction of critical raw materials outside Europe may lead to increased exposures to hazardous substances and psychosocial stressors in affected regions. Similarly, high upfront costs of energy technologies may disproportionately impact socioeconomically disadvantaged populations, potentially exacerbating health inequalities.

Therefore, while the energy transition offers substantial public health benefits, it is essential to ensure that it is safe, sustainable, and equitable. New technologies and novel materials must not only be green but also safe, requiring comprehensive understanding of exposome-wide impacts across the full life cycle of energy systems and how chemicals and environmental exposures affect biological systems.

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Research Needs

To understand and address the impact of the energy transition on the exposome, research needs to:

- To study the short- and long-term effects of occupational exposure to renewable energy industrial sites, including emerging risks from novel materials and processes, as well as exposures linked to decentralized systems and recycling activities (e.g. solar panels and batteries).
- To study the potential health outcomes (e.g. respiratory and cardiovascular diseases) of the transition from fossil fuels to renewable sources (e.g. hydrogen), including how new technologies may alter exposure profiles rather than fully eliminate harmful exposures, and considering specific impacts such as those related to wind energy systems and noise emissions (e.g. heat pumps).
- To incorporate the Safe and Sustainable by Design (SSbD) concept into the development of new energy technologies, ensuring that potential toxic and harmful exposures are mitigated, and supporting the integration of exposome-based risk assessment into sustainability frameworks (e.g. Life Cycle Assessment), including cumulative exposures from circular economy processes.

To assess the broader equity and global exposome implications of the energy transition, including how costs and access may affect vulnerable populations, and how the extraction and processing of critical raw materials outside Europe may shift environmental and health burdens.

Expected impact and policy relevance

This research will inform EU climate and energy policies, including the European Green Deal, Fit for 55 package, and Renewable Energy Directive, by ensuring that decarbonisation strategies maximise health co-benefits while minimising unintended exposures.

Findings will support the integration of health considerations into energy system design, industrial strategies, and innovation frameworks, including the Ecodesign for Sustainable Products Regulation and the Safe and Sustainable by Design (SSbD) initiative. Exposome-based evidence will strengthen regulatory approaches to emerging energy technologies, enabling more comprehensive assessment of chemical, physical, and occupational risks across their life cycle.

The research will contribute to the Just Transition Mechanism by identifying how energy transitions may differentially impact populations, supporting policies that ensure fair distribution of benefits and risks. This work aligns with SDG 3 (Good Health and Well-being), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action), supporting the development of energy systems that are both sustainable and health-protective.

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G2.2 Impact of mobility transition

Objective

To investigate the effects of the mobility transition on the exposome, considering how changes in transport systems reshape environmental exposures and the potential impacts on human health.

Relevance

The mobility transition in the EU is a cornerstone of the European Green Deal and the Sustainable and Smart Mobility Strategy, aiming to reduce transport-related greenhouse gas (GHG) emissions by 90% by 2050. Central to this vision are binding targets for zero-emission vehicles by 2035, the expansion of Sustainable Urban Mobility Plans (SUMPs), and industrial action plans that foster clean technologies. The transition away from fossil-fuel-based mobility emphasizes shifts towards active and public transport, electrification, and alternative fuels, while addressing social and economic impacts through mechanisms such as the Just Transition Mechanism.

Like the energy transition, the mobility transition profoundly reshapes the human exposome. It reduces tailpipe emissions and GHGs, while active transport increases physical activity and brings co-benefits for cardiovascular and metabolic health. However, potential adverse effects must also be acknowledged: heavier electric vehicles may increase brake and tyre-wear emissions; battery production requires rare metals with environmental and occupational health risks; and greater reliance on public transport may elevate exposure to communicable diseases.

In addition, mobility transitions interact with broader societal and environmental dynamics. The rapid growth of tourism and over-tourism can intensify transport-related exposures, placing additional pressure on local environments, infrastructure, and cultural ecosystems. Furthermore, the pace and nature of mobility transitions may differ globally, progressing faster in high-income countries than in low- and middle-income countries, potentially shifting environmental and health burdens.

These complex interactions underscore the need for systematic evaluation of new mobility concepts, technologies, and infrastructures—ensuring that health impacts are comprehensively assessed and that transitions are both sustainable and safe.

Research needs

Drawing on recent WHO (1), EEA/EU (2), and OECD/ITF (3) reports, the following priority areas emerge for research at the interface of mobility transition and the exposome:

- There is a need to develop integrated methods to capture air pollution (including non-exhaust PM), noise, heat, and physical activity during daily mobility. Promote community-based monitoring approaches, including personal and community air monitoring with transparent data ownership and feedback.
- There is a need to quantify tyre, brake, and road-wear emissions under real-world conditions, including from heavier EVs, and assess their composition, toxicity, and health effects to inform regulations such as Euro 7.
- There is a need to refine exposure–response functions for cardiovascular, metabolic, mental health, and cognitive outcomes, while evaluating interventions such as 30 km/h zones, low-noise tyres, and upgraded public transport systems.
- There is a need to strengthen tools such as WHO HEAT and ITHIM to quantify the health gains of walking, cycling, and public transport, while accounting for risks (injuries, infection), distributional effects, and uncertainty.

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- There is a need to integrate exposome indicators into SUMPs and related EU strategies; evaluate natural experiments (e.g. low-emission zones, street reallocations, pricing reforms) using robust causal designs.
- There is a need to focus on children, older adults, and low-income populations to map unequal burdens and benefits (air, noise, access to green space) and to ensure fair distribution of health outcomes.
- There is a need to develop interoperable data systems linking transport activity, exposures, and health, aligned with EU Zero Pollution and Green Deal targets to enable evidence-based and adaptive policymaking.
- There is a need to explore how mobility-related exposures intersect with other domains (e.g. food systems and urban environments), supporting the integration of exposome approaches into broader risk assessment frameworks beyond single-substance evaluation.

Expected impacts and SDGs

The Transport and Tourism (TRAN) Committee plays a pivotal role in translating research into policy. Through its mandate to guide the European Green Deal, the Fit for 55 package, SUMPs, the Mobility Transition Pathway, and fairness measures such as the Just Transition Mechanism, the Committee is uniquely positioned to ensure that mobility transition policies advance environmental objectives while safeguarding public health.

The ENVI Committee is central to ensuring that the health dimensions of the mobility transition are fully integrated into EU policymaking. Its oversight of the Zero Pollution Action Plan, the Air Quality Directives, and chemical safety regulations (e.g. REACH) provides a framework for addressing transport-related air pollution, noise, and chemical exposures from non-exhaust emissions and battery supply chains. Embedding exposome research within ENVI's agenda strengthens the evidence base for managing cumulative exposures and health inequalities.

The ITRE Committee is responsible for industrial policy, research, energy, and innovation, making it crucial in supporting the technological side of the mobility transition. Its mandate covers the EU Industrial Strategy, the European Battery Alliance, the Horizon Europe research programme, and the ESPR. By fostering innovation in clean mobility technologies—such as electrification, alternative fuels, and digital mobility systems—while embedding exposome research, ITRE can ensure that new materials, batteries, and technologies are not only green but also safe for human health and the environment.

By embedding exposome research into these frameworks, EU policies can maximize co-benefits, anticipate risks, and align with multiple Sustainable Development Goals (SDGs). In particular, they can advance SDG 3 (Good Health and Well-Being) by reducing harmful exposures and promoting active mobility, SDG 7 (Affordable and Clean Energy) by fostering clean and safe energy sources for transport, SDG 9 (Industry, Innovation and Infrastructure) by supporting sustainable and health-conscious technological innovation, SDG 11 (Sustainable Cities and Communities) by guiding healthier and more equitable urban mobility systems, and SDG 13 (Climate Action) by cutting transport-related greenhouse gas emissions and building climate resilience.

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G2.3 Impact of green transition (circular economy, chemical space)

Objective

The objective of this goal is to explore the impact of the green transition, particularly in terms of circular economy and chemical space on the exposome. By examining these transitions, the primary aim is to gain a comprehensive understanding of how shifts towards greener and sustainable practices affect the exposome, highlighting both negative and positive impacts.

Relevance

In 2019, the European Union (EU), through the European Green Deal (1), emphasized the need for a transition toward a circular, toxic-free and sustainable economy and enhance the competitiveness of the EU market. This transition has a crucial impact on the exposome, by promoting public health and eliminating harmful exposures. For instance, the transition toward renewable energy and resources aids the mitigation of air pollutants and greenhouse gas (GHG) emissions, leading to lower exposure to particulate matter and consequently lower rates of respiratory or cardiovascular effects (2).

While the transition to a circular economy, a key pillar of the green transition, aims to mitigate waste, reduce GHG, promote recycling, reuse, resource efficiency and adopt sustainable practices, it may also lead to challenges and unforeseen adverse health outcomes (1). The waste recycling and waste management options, for example, could pose some unintended health risks, such as exposure to hazardous waste, when they are not properly managed (3). Therefore, circular economy actions should be accompanied by a strategy of addressing and eliminating potential risks to human health and the environment, such as the Chemical Strategy for Sustainability (CSS) (4).

Moreover, the exploration and expansion of chemical space, including the substitution of hazardous chemicals with safer ones or the design of new molecules, may lead to unintended implications regarding the human exposure pathways, as the chemicals that humans are exposed to alters. In this context, it is important to consider key properties such as chemical persistence and mobility in the environment, as well as metabolic activation and deactivation processes, which influence exposure patterns and toxicological outcomes.

Therefore, both safety and sustainability aspects need to be integrated into this process, as the EC Safe and Sustainable by Design (SSbD) framework proposes (5,6). The integration of safety and sustainability concepts early in the (re)redesign process of a chemical or material considering the whole life cycle, will mitigate the potential negative impacts on human health, the environment and society, while adhering to circular economy principles (7). Recent research also highlights the importance of addressing occupational health risks in the context of the green transition, including emerging exposures linked to new materials and industrial processes (8).

To this end, it is imperative to explore and understand how these transitions may impact the exposome and their potential implications, ensuring that new risks will not be introduced, while maximizing the environmental health benefits. By analysing these interactions, Goal 2.3 aims to promote the integration of exposome science into the actions of green transition.

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Research needs

To improve the efficiency of green transition and address the impacts related to exposome, there is a need to integrate exposome science into this process to thoroughly identify and understand the associated risks. More specifically, there are research needs for:

- Integration of exposome-based risk assessment into environmental sustainability assessment methods (life cycle assessment): enhancing environmental impact assessment through life cycle assessment (LCA) coupled with exposome-based risk assessment to guide and support integrated impact assessment
- Investigation of aggregate and cumulative exposures from circular economy actions (e.g. waste recycling, waste management, and renewable energy)
- Incorporation of new chemicals, materials and products (e.g. biobased chemicals, biodegradable chemicals/materials, recycled materials) by developing new analytical and computational approaches
- Integration of exposome science into safe and sustainable by design practices (e.g. omics and system biology models to identify the chemical interactions with the biological system)
- Artificial Intelligence (AI)-assisted hazard assessment for early design to align with green transition/SDGs
- Evaluation of differential impacts of the green transition across populations, particularly communities that may face economic or logistical barriers, to guide equitable and supportive interventions
- Study exposome impacts in alternative economic models beyond highly industrialized systems, including community-led adaptation and local circular practices supporting sustainable and safe transitions

Expected impacts and SDG

Research on the integration of exposome research into the green transition, with a primary focus on circular economy and exploration of chemical space, will significantly impact the environment, innovation (SDG 9 – Industry, Innovation and Infrastructure), sustainable development (SDG12 – Responsible Consumption and Production) and public health (citizens, consumers, workers) and well-being (SDG3 – Good Health and Well-being). This integration will enhance the understanding of the interactions between humans and the totality of environmental exposures, fostering a human-centred and greener environment (SDG 13 – Climate Action), while also contributing to SDG 8 (Decent Work and Economic Growth) through improved occupational health and safety in green sectors**.**

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G2.4 Impact of food systems transition and sustainable farming

Objective

The objective of this goal is to examine how the transition of food systems towards sustainability, including practices such as regenerative agriculture, organic farming, agroecology, and sustainable intensification, impacts the exposome. This includes assessing how changes in food production, processing, distribution, and consumption influence human exposures across the life course. The goal is to identify both the health-promoting and potentially adverse consequences of sustainable farming and food system transitions on the exposome.

Relevance

The EU Farm to Fork Strategy, a key component of the European Green Deal, highlights the need for fair, healthy, and environmentally friendly food systems. Transitioning to sustainable farming and food systems is expected to reduce greenhouse gas emissions, promote biodiversity, minimize pesticide use, and reduce chemical inputs in agriculture, thereby decreasing harmful environmental exposures. This transition can also promote healthier diets by increasing the availability of nutritious, safe, and sustainable foods, thus supporting population health.

However, food system transitions may also introduce new exposure pathways or modify existing ones. For example, reduced pesticide use might lower certain toxic exposures but could lead to increased reliance on biocontrol agents or novel bio-based products, whose long-term effects on the exposome remain underexplored. Similarly, practices such as waste valorization, use of recycled organic fertilizers, or novel food proteins (e.g. insect-based, cultured meat) may introduce emerging risks that need to be thoroughly assessed. In addition, the use of recycled materials in food contact materials may introduce non-intentionally added substances (NIAS) into the food chain, representing an emerging exposure concern. Sustainable farming and dietary shifts (e.g. more plant-based diets) can also alter the nutritional exposome, microbiome interactions, and susceptibility to disease.

At the global level, food system transitions are highly heterogeneous. In low- and middle-income countries (LMICs), rapid urbanization and dietary shifts towards ultra-processed foods are contributing to a double

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burden of malnutrition, while climate change disproportionately affects food systems, food security, and livelihoods dependent on agriculture.

Therefore, integrating exposome science into food system and farming transitions is essential to maximize benefits for health and sustainability while minimizing unintended risks.

Research needs

To support the integration of exposome science into sustainable food systems and farming, the following research needs were identified:

- Development of exposome-based methodologies to assess cumulative exposures from food, farming environments, and food chain processes
- Assessment of unintended exposures arising from bio-based inputs, biopesticides, recycled fertilizers, and novel foods, including non-intentionally added substances (NIAS) from recycled food contact materials
- Exploration of the link between nutritional exposome (diet, microbiome, metabolites) and sustainable dietary transitions, including shifts towards ultra-processed foods and associated health impacts
- Integration of exposome approaches into food safety and risk assessment frameworks, beyond single-substance evaluation
- Use of advanced analytics (omics, big data, AI) to characterize chemical and biological exposure mixtures in farming and food environments, including high-throughput approaches to monitor contaminants such as mycotoxins and pesticide residues and link them to metabolic exposome markers
- Life cycle and systems-based approaches to evaluate trade-offs between reduced environmental footprints and potential new health exposures

Expected impacts and SDG

By integrating exposome science into the transition of food systems and sustainable farming, this research will contribute to:

- Improved public health and well-being through healthier diets and reduced harmful exposures (SDG 3 – Good Health and Well-being).
- Sustainable food production and consumption practices that safeguard both the environment and consumers (SDG 12 – Responsible Consumption and Production).
- Protection of ecosystems and biodiversity through sustainable agriculture (SDG 15 – Life on Land).
- Climate action through the mitigation of agricultural greenhouse gas emissions and resilient food systems (SDG 13 – Climate Action).

This goal will ensure that the shift to sustainable food systems maximizes benefits for both the environment and human health, while avoiding the introduction of new risks into the exposome.

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G2.5 Impact of transition in work conditions

Objective

To investigate how transitions in work conditions reshape the exposome of workers and influence health and well-being across the life course.

Relevance

A person's working life is one of the most significant contributors to long-term health and well-being. Most individuals spend at least 40 years in the workforce, typically 8 hours a day, 5 days a week. These decades of occupational exposure overlap with critical life stages, including reproductive years, midlife, and aging. Beyond direct workplace exposures, employment is also closely tied to lifestyle habits (e.g. diet, physical activity, smoking, alcohol use) and socioeconomic status, all of which strongly shape health outcomes.

Today, the rapid transformation of working conditions—driven by industrial innovation, digitalization, the green transition, and new employment models—is reshaping the nature and intensity of occupational exposures. Workers are no longer only exposed to well-recognized hazards (e.g. dusts, solvents, diesel exhaust), but also to novel risks from new materials, chemicals, and psychosocial stressors associated with emerging work environments (e.g. remote work, platform-based jobs, automation). Traditional single-exposure risk assessments are insufficient to capture this evolving complexity.

Research needs

Integrating exposomics into occupational health research offers a modernized, holistic approach to understanding how changing work conditions affect health across the life course. This approach can provide early warning of new and cumulative risks, improve prevention strategies, and inform regulations that keep pace with workplace transformations. Integrating exposomics into this transition is critical, with four priority research areas:

- Future research must explicitly capture transitions in work conditions—from heavy industry to green technologies, from office-based to remote work, and from stable to precarious employment models. These transitions may alter both chemical exposures (e.g. solvents, combustion products, nanomaterials) and non-chemical exposures (e.g. psychosocial stress, sedentary behaviour, disrupted circadian rhythms). The rise of precarious employment further complicates the assessment of exposure patterns over time. Scaling up transition-focused cohorts will enable early identification of new risks, better protection of vulnerable worker populations, and guidance for adaptive workplace regulations. Specific attention should be given to the health impacts of remote and digital work, including increased screen time, sleep disruption, metabolic risks, and erosion of work–life boundaries.
- While shift work is linked to cardiovascular disease and breast cancer, how night work combines with chemical exposures (e.g., solvents, endocrine disruptors) or chronic stress remains unclear. Research should move beyond single-hazard studies toward integrated models of cumulative exposures, using biological response data (omics, effect biomarkers) to generate actionable prevention strategies.
- Current occupational exposure limits are based on traditional toxicology and epidemiology and rarely reflect long-term, low-dose, or mixture effects. Exposomics can provide the evidence base for next-generation workplace safety standards by identifying early biological signals of harm, characterizing vulnerable subgroups, and highlighting risks not captured by current monitoring. For example, exposome data could inform safer substitution in green industries, guide interventions in platform-based gig work (e.g. air pollution exposure for delivery workers), and integrate psychosocial risks (e.g.

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low job control, precarious contracts) into regulatory frameworks. Ultimately, exposome-informed policy will allow regulations to evolve in parallel with changing work environments.

- Additional research should assess resilience and adaptive capacity among workers, identifying protective factors (e.g. coping skills and social support) that explain why some individuals better adapt to changing work environments. Furthermore, studies should investigate the cognitive and emotional impacts of screen-based and AI-mediated work, including attention fatigue, decision overload, and social isolation. Combining objective and subjective measures (e.g. working hours vs perceived workload) will be essential to distinguish external exposures from perceived stressors and to inform workplace policy. Special attention should also be given to vulnerable populations, including workers in informal economies and settlements, using low-cost and community-based monitoring approaches.

Expected Impacts and SDGs

Integrating exposome science into occupational health during transitions in working conditions will:

- Improve disease prevention and workforce well-being (SDG 3 – Good Health and Well-being).
- Support innovation and adaptation in occupational safety frameworks (SDG 9 – Industry, Innovation and Infrastructure).
- Contribute to sustainable, fair, and safe employment models (SDG 8 – Decent Work and Economic Growth).
- Enhance resilience to environmental and social challenges (SDG 10 – Reduced Inequalities).

This goal will ensure that the future of work is not only more productive and sustainable, but also healthier and safer for all workers across their life course.

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G3 How can the exposome support public health policy/regulation

This goal focuses on understanding how policies and regulations aimed at improving health and environments can benefit from considering the effect of cumulative exposure to various risks. It further explores how the exposome approach, by targeting a variety of exposure factors that impact health and well-being, could embed a holistic vision of health into policy design. Here we propose to precise the definition of the exposome and its extent to further reflect on certain social aspects of exposure to build public policies adapted to population needs.

Whether focusing on how exposome research can benefit burden of disease assessment, urban design, chemical regulation, public health recommendations and communication, or even social transformation, we note that there's a need to harmonize data to understand all the interactions between different areas and sectors where individuals are exposed, as well as different types of exposure. The concept of exposome can therefore be a way to raise awareness of researchers, decision makers and individuals on the necessity of decompartmentalizing science exposure, notably environmental and occupational health subjects, and start considering plural exposure and their interaction to understand the impact of the environment on human health.

G3.1 Reassessing burden of disease, socio-economic costs and economic impact on life quality

Objective

To understand how exposures contribute to disease risk and to integrate their effect in the burden of disease assessment.

Relevance

In 2012, WHO estimated that 12.6 million deaths each year were caused by unhealthy environments. Environmental risk factors included air, water and soil pollution, chemical exposures and other factors associated with NCDs (1). With an increasing number of diseases linked to exposures in the environment (natural and built), more cost-effective interventions are introduced as part of evidence based-policies. Assessing the burden of disease, by quantifying various impacts of diseases, contributes to choosing these interventions.

This evaluation takes into account different aspects of the cost of a disease: direct costs (medical and non-medical expenses such as consultations, drug treatments, medico-social services), indirect costs (reduced work capacity, absenteeism) and intangible costs (effects on quality of life, years of life lost due to premature death). Therefore, a better understanding of the global cost of a disease (including the cost for society and broader well-being) can help policymakers with decision-making, prioritization of interventions and evaluation of preventive measures.

By identifying the exposures that can cause diseases, the exposome approach can help policymakers better assess the health burden and potentially reduce it by targeting avoidable and modifiable exposure factors. As an example, non-communicable diseases illustrate the extent of the socio-economic costs and impact on quality of life. These diseases, which are largely explained by exposure to environmental factors (e.g. air pollution, exposure to chemicals, and lifestyle), are among the most costly for healthcare systems and the whole community. For instance, NCDs including chronic respiratory disease, cardiovascular disease, mental health, diabetes and cancer were estimated to cause a global cumulative economic loss of $47 trillion between 2011 and 2030 (2).

However, while socio-economic quantification of exposure's impacts can be a driving force for action, it is important to consider that even with evidence showing the cost-effectiveness of an intervention or the high

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cost of inaction, translation into public action remains dependent on structural variables such as political processes of agenda-setting or dialogue between researchers and policymakers.

Research needs

To understand and address the burden of disease, socio-economic costs, and impacts on quality of life, research needs to:

- Integrate exposure risk into indicators of well-being
- Develop burden of disease data in LMICs and provide a more accurate estimate of the impact of the burden for different economies and populations
- Link burden of disease and cost-benefit analyses on public management choices/options in order to better understand the costs of decisions
- Better biomonitoring, environmental monitoring, and wearable device application for systematic exposome measurement
- Estimate exposure limits and links to related environmental policies
- Design interventions to reduce harmful exposures and measure return on investment to convince policymakers
- Reveal disparities in exposome between communities and populations in order to have a broader vision of cost-benefit analysis on the planetary level
- Develop economic and causal modelling tools to attribute impacts of complex mixtures
- Explore the implications for attributable risk fractions and compensation systems
- Examine why scientific evidence often fails to translate into policy action, with particular attention to the role of regulatory capture and the potential for communities to leverage economic arguments to strengthen accountability mechanisms
- Create population-based longitudinal cohorts and standardized exposure-outcome frameworks that integrate non-targeted exposomics, multi-omics biomarkers, and socio-economic outcomes

Expected impact and policy relevance

Integrating exposome data into burden of disease assessments will improve the accuracy of health and socio-economic impact estimates linked to environmental exposures, including cumulative and life-course effects. This will enable policymakers to better prioritise preventive actions and allocate resources based on the true costs of disease and the benefits of exposure reduction.

The results will directly support the development, revision, and implementation of EU regulatory frameworks by strengthening the evidence linking exposures to health outcomes. In particular, they will inform policies under the European Green Deal, the Zero Pollution Action Plan, and the Chemicals Strategy for Sustainability, as well as sectoral regulations on air quality, food safety, consumer products, and occupational health.

By improving cost–benefit and cost-effectiveness analyses, this work will support more robust regulatory impact assessments, quantify the economic benefits of interventions, and highlight the costs of inaction. It will also strengthen alignment with global frameworks, including WHO guidelines and the Global Burden of Disease initiative.

This research contributes to the Sustainable Development Goals, particularly SDG 3 (Good Health and Well-being), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), by supporting policies that reduce harmful exposures and promote healthier and more sustainable environments.

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G3.2 Revisiting urban design, housing, workplace

Objective

To consider various exposures to make buildings, public spaces, and infrastructures safer and to promote better health and well-being by identifying exposures with positive impacts, in relation to the design of territorial and urban planning policies.

Relevance

Research increasingly shows how urban and territorial planning shape health outcomes. Therefore, it has become evident that policies aimed at reducing the negative impacts of environmental exposures need to consider a multitude of living environments (e.g. public spaces, habitats, and workplaces) and their characteristics to prevent risks and ensure the well-being of populations. With a strong emphasis on indoor environments, as that is where people are increasingly spending most of their most time.

Urbanization and the increase in urban populations that characterize our century has raised many issues that exposome studies need to address. More than half of the global population now lives in urban areas (1). The way that cities are designed including houses and workplaces can directly affect the well-being of their population. Exposure to chemicals, such as dust and gases in certain jobs (manufacturing, mining) can lead to cancers and respiratory disease. Physical exposures to noise can provoke stress and cardiovascular disease. Exposure to vibrations could affect musculoskeletal health. Biological factors such as bacteria, viruses and allergens can trigger respiratory diseases among other infectious diseases.

Other aspects of the urban exposome also play a role such as:

- Access to facilities and essential infrastructures (e.g. transportation, bicycle lanes, healthcare facilities, water distribution networks)
- Proximity to industrial zones
- Access to green and blue spaces
- Urban density and overcrowding that can accelerate the propagation of communicable diseases
- Exposure to stress and psychosocial risks
- Spatial and social segregation leading to unequal access to resources protecting the health of individuals
- Increased vulnerability to risks and inequalities. An example of these inequalities in exposure is the concentration of the most disadvantaged populations in neighbourhoods exposed to higher temperatures (2). There are also differences in the distribution of risks between countries).
- Exposures associated with indoor environments (e.g. air pollution and toxicity of certain cleaning products)

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The urban exposome can therefore be a good way to understand the health of individuals and populations by considering various environments that surround them. By identifying a plurality of exposures and understanding the interaction between them, as well as how this affects people' lives and life-long health (for example through biomarkers of exposures and participatory approaches in collecting data), the exposome can serve as a lever for creating more sustainable and healthier environments. For instance, the exposome can be integrated into risk assessment by including areas and populations most at risk in cartographies monitoring various exposures and their evolution (e.g. air quality, climate change effects, and noise pollution).

By encouraging local authorities and policymakers to consider urban planning through the exposome paradigm, exposome research can represent an effective way to act on and reduce negative urban exposures, keeping in mind the dynamic character of the environment and the temporality of political agenda-setting.

Research needs

To understand and address the impact of urban design, housing, and workplaces on the exposome, research needs to:

- Develop tools and approaches for participatory environmental health research to collect data on different exposures in social and spatial environments (including workplaces)
- Develop monitoring devices and sensors allowing for the tracking of exposures (such as air pollution, heat, chemical substances) in real time and their effect. These devices can be used for research purposes by collecting data on exposure as well as a tool for prevention by training participants to collect and interpret results, while taking ownership over the process. Attention must therefore be drawn to ensure the equality of access to these tools and sensors
- Understand causalities between environmental pollutants and health outcomes by combining findings from multiple fields (e.g. epidemiology, toxicology, social sciences, biology, immunology) and mobilising different sources of data. Considering that establishing causality can be challenging, spaces for interdisciplinary dialogue should be created to advance thinking on causal relationships and to reflect on methods for bringing together data across disciplines.
- Develop cost-benefit analyses on urban policies considering exposure prevention and management
- Develop knowledge on exposure and co-exposure in schools
- Develop research on the effects of nanomaterials on health and environment
- Better understanding of socio-economic, environmental and health impacts of global change and soil pollution
- Develop boundary objects like for instance risk cartographies and other common data base and indicators to build and share knowledge on exposure that can be built upon for urban planning
- Map emerging pollutants (e.g. PFAS and microplastics)
- Investigate how rising indoor temperatures influence the concentrations of endocrine-disrupting chemicals in indoor air

Expected impact and policy relevance

Revisiting urban design, housing, and workplaces through an exposome perspective will strengthen the evidence base for policies aimed at reducing harmful exposures and promoting healthier living and working environments. This will support the design and implementation of integrated interventions addressing air quality, noise, housing conditions, and access to green and healthy spaces.

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The findings will directly inform EU regulatory and policy frameworks, including the European Green Deal, the Urban Agenda for the EU, the 8th Environment Action Programme, the Environmental Noise Directive, and the EU Strategic Framework on Health and Safety at Work. They will also support the development of urban planning, housing, and occupational health regulations that better account for cumulative and interacting exposures.

At the international level, this work aligns with WHO initiatives on healthy cities and urban health, and contributes to global agendas such as UN-Habitat. It supports the achievement of SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), and SDG 11 (Sustainable Cities and Communities) by promoting environments that reduce exposure risks and improve quality of life.

Overall, this research will facilitate the translation of exposome evidence into urban, housing, and workplace policies, enabling more preventive, health-protective, and sustainable regulatory approaches.

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G3.3 Impact on chemical, physical regulations

Objective

Investigate how exposome research is influencing chemical and physical risk assessment and regulation, and how this knowledge can support more holistic, harmonized, and preventive regulatory frameworks in Europe.

Relevance

Exposome science provides a comprehensive framework that challenges current compartmentalized approaches to risk assessment and management. By considering the full range of exposures—chemical, physical, and environmental—across the life course and across multiple sources and settings, it enables a more realistic understanding of risks to human health.

Chemical dimension

There is growing concern regarding exposure to complex mixtures of chemicals and their cumulative health effects. Current EU regulatory frameworks, including those implemented by EFSA and ECHA, primarily assess individual substances or limited groups of similar chemicals, often separating exposure pathways such as food, consumer products, and occupational environments. However, for many substances (e.g. PFAS, heavy metals, pesticides), combined exposures across these domains are critical in determining overall risk.

The Chemicals Strategy for Sustainability (CSS) is driving the transition towards more integrated approaches (1). It promotes the development and implementation of mixture risk assessment (MRA), harmonisation across regulatory frameworks (e.g. REACH, CLP, pesticides, biocides), and the use of alternative methods such as in silico, in vitro, and AI-based tools. Initiatives such as the RACEMiC roadmap (2) and ExpoAdvance project (3) aim to advance harmonised methodologies and improve aggregate exposure assessment.

The “one substance, one assessment” approach (4) further supports regulatory coherence by streamlining chemical assessments across EU agencies, improving data sharing, and enabling the development of a Common Data Platform, including human biomonitoring data from programmes such as HBM4EU and PARC. These developments contribute to more preventive and health-protective regulatory frameworks that better reflect real-world exposures.

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Physical dimension

Physical exposures—including noise, vibration, radiation, and heat—are also regulated at EU level but are typically assessed independently using hazard- or threshold-based approaches. These exposures are associated with a range of adverse health outcomes, including cardiovascular, neurological, and reproductive effects.

However, in real-world conditions, health risks arise from combined and interacting exposures. For example, co-exposure to noise and chemicals may increase the risk of hearing loss, while heat stress can amplify the effects of air pollution. Integrating exposome approaches into regulatory frameworks would enable a more comprehensive assessment of cumulative risks across exposure domains.

Research needs

To understand and address the impact of chemical and physical regulations on the exposome, research needs to:

- Assessment methods across chemical and physical domains
- Expand tools to integrate multiple sources, routes, and types of exposures (e.g. combined chemical and noise exposure)
- Strengthen collection, sharing, and interoperability of exposure data across EU agencies (e.g. Common Data Platform for chemical and physical monitoring; HBM data linked with environmental and occupational data)
- Develop advanced computational models (including AI) to estimate combined chemical and physical exposures and their health outcomes
- Ensure research results directly inform risk management measures, including revising occupational exposure limits and environmental quality standards.
- Introduce or strengthen provisions for combined effects in regulations across sectors (e.g. diet, water, air, toys, cosmetics, detergents, electromagnetic fields, noise)
- Promote scientific and structural reforms to embed exposome approaches in EU agencies and national authorities. Encourage partnerships with local communities to build their capacity to use exposome approaches for environmental health awareness and action, while also incorporating their perspectives on the impacts of physical exposures (e.g. the psychosocial effects of noise pollution)

Expected impact and policy relevance

Exposome-informed approaches will enhance EU regulatory frameworks by:

- Supporting the Chemical Strategy for Sustainability, REACH revision, PFAS restriction, and One Substance One Assessment.

- Informing updates to physical exposure regulations (e.g. noise, EMF, radiation, vibration, heat, and light) with evidence on cumulative and interactive health effects.

- Strengthening occupational and environmental health protection by integrating chemical and physical exposures into holistic assessments.

Guiding more preventive and harmonized regulation, better aligned with real-world exposure scenarios and the EU ambition of a toxic-free environment.

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G3.4 Impact on public health recommendations and communication

Objective

To integrate recent knowledge about exposome research into public health recommendations, prevention and awareness raising campaigns, and its faculty to take into account various and cumulative exposures and their potential risks for human health.

Relevance

Growing evidence from public health research highlights the importance of addressing avoidable environmental and social factors that influence health and contribute to disease. The exposome approach provides new insights into the complex mechanisms linking exposures to health outcomes, including their role in shaping health inequalities (1). These advances can help shorten the gap between scientific knowledge and preventive action.

To fully realise this potential, public health strategies and communication must integrate exposome-based evidence. Effective communication requires tailoring messages to different audiences, with particular attention to health literacy. This includes using education systems, NGOs, and participatory platforms to raise awareness of cumulative exposures and to foster engagement among individuals, communities, and decision-makers.

The integration of the exposome into medical training and clinical practice can further strengthen prevention by enabling more targeted and personalised recommendations. Health professionals, alongside local authorities and other stakeholders, play a key role in translating knowledge into action, particularly during critical life stages such as pregnancy and childhood, where exposure risks are more visible and policy attention is heightened.

At the same time, communication of exposome data must be carefully managed. While individuals have a right to information about their exposures, they may lack the capacity to act on it. Poorly designed messages may lead to anxiety or unintended behavioural responses (2). Public health communication should therefore balance awareness-raising with practical guidance, avoiding individual blame and emphasising the role of collective action and regulatory measures.

The exposome approach also highlights the need to address trade-offs in health recommendations. For example, promoting physical activity or healthy diets may simultaneously increase exposure to air pollution or pesticide residues. A more integrated perspective is therefore required to ensure that recommendations maximise overall health benefits.

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Overall, the exposome complements existing health determinants frameworks by providing a more holistic understanding of how multiple exposures interact across the life course. This supports the development of more effective, preventive, and equitable public health strategies.

Research needs

To enhance the integration of exposome into public policies, exposome research needs to:

- Adapt communication strategies for non-academic audiences specially on methods and results, in order to improve knowledge and promote healthier lifestyles. More broadly, develop tailored and accessible communication targeting vulnerable groups
- Develop more detailed research aimed at understanding the impact of lifelong and early life exposures on health outcomes by conducting longitudinal studies and temporal profiling
- Develop knowledge on disease aetiology and notably environmental origins of diseases
- Identify periods of vulnerability (e.g. pregnancy and childhood) and time periods of exposure that are most important to work on
- Identify obstacles to the decompartmentalization of environmental and occupational health
- Improve knowledge on the pathways of exposures (aggregated exposure pathways) to support evidence-based policies that aim to reduce harmful exposures
- Follow and integrate the legal dimension to the exposome by redefining responsibilities (either for adding pollution, or for failing to act against it.)
- Integrate the One Health approach linking different disciplines to get joint input and more research on non-pharmacological health interventions
- Assess the effectiveness of public health campaigns based on implementation research and by trying to translate the objectives of these campaigns into performance indicators
- Develop methods or strategies to identify and combat campaigns, in particular on social media, that spread health misinformation
- Develop knowledge about how workdays impact lifestyle recommendations

Expected impact and policy relevance

Integrating exposome research into public health recommendations and communication strategies will strengthen the evidence base for prevention policies by linking environmental exposures to health outcomes and behaviours. This will support the design of more effective, targeted, and equitable interventions, while improving risk communication and public engagement.

The findings will inform the development and implementation of EU and international public health frameworks, including cancer prevention strategies and non-communicable disease policies, by incorporating cumulative and life-course exposures into recommendations. They will also support regulatory and policy actions aimed at reducing harmful exposures and promoting healthier environments.

This work contributes to global health priorities, including SDG 3 (Good Health and Well-being), and aligns with WHO strategies on non-communicable diseases and risk factor reduction.

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G3.5 Exposome-inspired health promotion

Objective

To explore the positive impacts linked to certain exposures and investigate how exposome research can encourage adopting a holistic vision of health and well-being. To use exposome knowledge for health promotion and beyond traditional prevention.

Relevance

Integrating exposome research into public policies and regulations offers the potential to reduce harmful exposures while identifying those that promote health and well-being. By adopting a broad definition of exposures, the exposome shifts the focus from disease and risk management towards a more holistic understanding of health, including factors that support resilience and quality of life.

Emerging evidence on positive health determinants highlights opportunities to embed preventive and health-promoting approaches into policy. In particular, the socio-exposome perspective emphasises environmental and social justice by addressing inequalities in exposure and the capacity to mitigate risks (1). The use of socio-markers—measurable indicators of social conditions—can support policies aimed at identifying structural drivers of health inequalities and guiding multisectoral interventions.

Certain exposures are known to have beneficial effects on health and can inform public policy. These include physical activity, healthy diets, and access to green and blue spaces, which contribute to improved physical, mental, and cognitive health (2). Exposome research can help identify and quantify these positive exposures, supporting policies that promote access to healthy environments, sustainable food systems, and community well-being.

At the same time, communication strategies must be carefully designed. While a positive framing of the exposome can support stakeholder engagement and policy uptake, it may be interpreted differently across audiences and may obscure the importance of reducing harmful exposures. A balanced approach is therefore needed, recognising that health gains often result from both enhancing beneficial exposures and reducing harmful ones.

Overall, aligning the exposome with health promotion approaches can support the development of more integrated policies that not only reduce health risks but also improve living conditions and reduce health inequalities.

Research needs

To enhance the integration of exposome into public policies, exposome research needs to:

- Incorporate aspects related to socioeconomic factors, social determinants of health, and inequalities into biomedical research to gain a global perspective on what contributes to health and how to improve it
- Develop transdisciplinary actions for better living conditions (linked to housing and mobility policies) and conduct further research on the factors that contribute to creating and maintaining healthy and habitable territories
- Better benefit/risk assessment by integrating risk perception and developing a common metric for benefit/risk and pleasure/risk assessment and more broadly metrics for the positive exposome
- Develop positive indicators linked to workplaces
- Specify the conceptual framework around a potential positive approach to the exposome

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- Further study what type of green and blue areas that are best for population health (type of trees, grass, ponds, canals) taking into accounts all impacts of each solution (decreased heat, respiratory health, allergies)
- Take into account mental health impacts in different designs (urban, rural, workplace)
- Social and digital exposome: Develop public health recommendations for increased social interactions while maintaining benefits of digitalisation
- Further develop exposome signatures (including social and molecular) of healthy people
- Further exposome studies about the impact of healthy diets (quantify biomarkers with demonstrated positive effects)

Expected impact and policy relevance

Integrating exposome research into health promotion will strengthen policies aimed at improving well-being by combining the reduction of harmful exposures with the enhancement of beneficial ones. This approach will support the development of more holistic, preventive, and equity-oriented public health strategies.

The findings will inform EU and national policies by providing evidence on how environmental, social, and behavioural exposures contribute to positive health outcomes. This will support the design of interventions in areas such as urban planning, food systems, biodiversity, and workplace health, ensuring that policies promote healthier living conditions while reducing inequalities.

Exposome-informed health promotion will also improve policy coherence across sectors by linking health, environmental, and social objectives. It will contribute to the implementation of key EU frameworks, including EU4Health and the EU Biodiversity Strategy for 2030, by integrating health co-benefits into broader sustainability policies.

At the global level, this work supports the achievement of SDG 3 (Good Health and Well-being) and SDG 10 (Reduced Inequalities) by promoting environments and policies that enhance population health and reduce disparities.

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G4 How can the exposome improve medicine

This goal aims to investigate how exposome science will enhance medicine by offering actionable insights into disease incidence, patient care, and management. By integrating exposome data (e.g. environment, working, psychosocial, lifestyle, behaviours) into medical research and practice, we will understand with better precision the role and how to mitigate the interplay between environmental exposures, lifestyle factors, social factors, and therapeutic interventions.

Medicine is moving towards data-driven approaches drawing on real-world evidence, yet exposures related to environmental, social, and lifestyle remain largely underrepresented in clinical research and practice. This exposome information is often considered as confounding factors, which underscores its possible causal effect on diseases. The exposome offers comprehensive sets of methods to characterise, quantify, and dissect these external and internal effects across the life course, allowing clinicians and researchers to:

- Identify how exposures shape disease trajectories,
- Understand how exposures influence prognosis and treatment outcomes, while considering population stratification to better identify and address vulnerable groups,
- Integrate exposure information into screening and monitoring programmes,
- Use pharmaco-exposomics to uncover drug–exposure interactions that modulate drug metabolism and influence drug safety, response, and occurrences of adverse reactions,
- Promote the development of personal exposome-based sensors to support precision-based prevention and health promotion.

The integration of exposomics and exposome domains will be critical to unravel why individuals with comparable genetic predisposition or physician-based diagnosis differentially respond to treatments or experience different disease trajectories.

The focus of the subgoals will be on

- **Pharmaco-exposomics**: Study how chronic and acute exposures (e.g. co-exposure to chemicals including drugs, diet, microbiome, lifestyle, heat waves) interact with drugs, influencing metabolism, response, and side effects.
- **Risk stratification tools:** Integrate exposome-derived biomarkers and data into patient stratification models to predict susceptibility, prognosis, and treatment response.
- **Screening and monitoring programmes:** Incorporate exposure signatures into population- and patient-level screening strategies to improve detection of high-risk groups and optimize follow-up.
- **Outcome research:** Investigate how lifetime exposures influence recovery, complications and long-term health outcomes, with the aim of identifying modifiable targets for prevention and intervention studies in chronic and acute diseases (e.g. cardiovascular disease, cancer, metabolic disorders).
- **Clinical data integration**: Link exposome datasets with electronic health records and clinical cohorts, enabling routine use of exposure data in hospital and clinical workflows.
- **Clinical grade personal exposome monitors**: Promoting innovation in the development of equitable personal sensors of the exposome.

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G4.1 The exposome and precision prevention

Objective

With the aim of preventing disease onset, progression, and recurrence, precision prevention methodologies adopt holistic approaches for risk stratified subpopulations - delivering timely, effective and equitable interventions, whether for healthy individuals, those at high-risk, or those living with chronic disease. Human exposomics tools integrating all environmental, social, lifestyle and cultural factors, including the endogenous biological response and genetic information would revolutionize the implementation and capacity-building of precision prevention models.

Relevance

Strengthening prevention is a key priority for European health systems, as highlighted in the State of Health in the EU report (1), particularly to reduce the growing health and economic burden of non-communicable diseases (NCDs). Precision prevention aims to move beyond population-average approaches by identifying risk profiles in specific subpopulations and delivering more targeted, timely, and effective interventions.

While definitions vary, precision prevention generally refers to the use of biological, environmental, behavioural, and socio-economic data to tailor prevention strategies to individuals or groups (2). Current initiatives in Europe, such as the 1+Million Genomes (1+MG) initiative and the Genome of Europe project, reflect major investments in genomic data infrastructures to support personalised healthcare.

However, most existing precision prevention approaches remain largely focused on genetic and molecular data, with limited integration of environmental and social determinants. Given that many chronic diseases are strongly influenced by environmental and lifestyle factors, incorporating the exposome is essential to improve the accuracy, relevance, and equity of prevention strategies.

The exposome framework enables a more comprehensive understanding of disease risk by capturing the dynamic interactions between environmental exposures and biological responses across the life course. It also provides an opportunity to better account for variability between and within populations, including differences linked to socio-economic conditions and living environments.

Integrating exposome data into precision prevention can therefore enhance the identification of at-risk groups, improve early detection strategies, and support more effective interventions across primary, secondary, and tertiary prevention. It also aligns with ongoing developments in digital health, data integration, and personalised medicine, including initiatives such as the European Health Data Space.

Overall, combining genomic and exposomic approaches represents a critical step towards more holistic, data-driven, and equitable prevention models that better reflect real-world determinants of health.

Research needs

To leverage exposome research for advancing precision prevention strategies, research needs to:

- Novel exposomic study designs prospectively collecting and accessing repeated measures within critical windows of susceptibility for different disease risk groups using exposomics tools that complement genetic information
- Larger and longer prospective exposome studies integrating genetic information with access to biosamples and molecular epidemiological markers prior to disease symptoms appearance across lifetime (e.g. how early life and in utero exposures might affect therapeutic responses later in life)
- Larger and longitudinal non-pharmacological health intervention trials with greater representation of at-risk subpopulations and their disease risk stratified exposomic/genetic characteristics

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- Harmonized datasets to estimate and compare the attributable disease burden across sub-populations for novel risk factors associated with chronic diseases across countries.
- Standardized protocols of multi-omics platforms and biomarkers of exposure/effect integrating exposomic datasets with gene expression (including epigenetics) omics platforms would unveil mechanisms and biological pathways of disease development (e.g. cancer) from early-stage processes (e.g. immune response) to disease development and progression in time and space Similarly, multi-omics and biomarkers would feed into better understanding chronic disease control mechanisms for specific subpopulations sharing common environmental risk factors, accounting for ethical concerns, inequalities, socioeconomic position, and other contextual factors .
- Greater understanding of how the daily environments of individuals and subgroups interact with gene expression, epigenetics, and chronic disease development (cancer).
- Human exposomics tools would facilitate the research to market implementation process by providing critical information on the efficacy of novel non-pharmacological health interventions, as part of a comprehensive health technology assessment (HTA), accounting for societal, economic, efficiency and other contextual factors.
- Multi omics-based pharmaco-exposomics would help understand how environment affects drug metabolism, efficacy and therapeutic outcomes, improving pharmaceutical drug efficacy and efficiency, while improving clinical trial design, better predict patient response to treatment, ensuring equitable exposome-informed clinical practice.
- Develop interventions and exposomic toolboxes to mitigate environmental exposures that negatively influence disease prognosis or interfere with the effectiveness of standard medications.
- The performance and contextual characteristics including any side effects of precision prevention and control models for select subpopulations would be best supported by exposomics tools on advanced (digital) health technologies, such as medical devices, engineered biosensors, circadian clock-based therapeutics, organ-on-chip models, and high-throughput screening platforms, to enable faster, cost-effective, and real-time detection of exposure-related health risks.
- Advances in wearable sensors, mobile apps, environmental sensors, biomarkers, and electronic medical records linkages to enable continuous, real-time assessment of environmental exposures and their biological effects in disease risk stratified groups and disease stages.

Expected impacts

Precision prevention informed by exposome research will enable a shift from population-average approaches to more targeted, data-driven prevention strategies, improving the effectiveness and efficiency of health interventions across the life course.

Integrating genomic, environmental, and social data will strengthen the identification of at-risk populations and support the development of tailored interventions, improving disease prevention, early detection, and management while reducing adverse treatment effects. This approach will contribute to more equitable health outcomes by better accounting for differences in exposures across populations.

The results will support the implementation of EU initiatives on personalised medicine and digital health, including the European Health Data Space and the 1+Million Genomes initiative, by enhancing the integration of environmental data into health systems and decision-making processes. They will also inform Health Technology Assessment (HTA) frameworks by improving the evaluation of preventive interventions and non-pharmacological strategies.

At a broader level, this work will contribute to reducing the burden of non-communicable diseases and associated socio-economic costs, supporting EU health system sustainability and competitiveness. It aligns

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with SDG 3 (Good Health and Well-being) and SDG 9 (Industry, Innovation and Infrastructure) by promoting innovative, preventive, and personalised health approaches.

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G4.2 Integrating genome and exposome in medicine

Objective

To highlight the significance and the unmet research needs addressing the intersection of genomic and exposome sciences and foster data for healthcare and medical innovations. Through transdisciplinary integration we foresee a deep understanding of health and disease trajectories, facilitating personalized risk assessment, and advance precision treatment strategies.

Relevance

A person's health and their capacity to recover from diseases is defined though environmental and genetic causes. Genomics and exposome science and data need cross-contamination. These genetic and environmental causes for diseases are not mutually exclusive. They rather reflect balance and dynamic interplay across genomic and exposomic effects upon health.

There are multiple motivations to foster the combination of genomic and exposomic into ambitious research programmes. First and foremost, we must allow scientific environments, infrastructures and training projects that will encourage trans-disciplinarity and reduce the competition between genomic and exposome research fields. Combining genome- and exposome-wide approaches will empower clinical research. This will concern both rare and chronic disease and disorders. The integration will advance precision medicine, facilitates the early detection of real-life exposure mixture effects on human health and emerging risks, and guides the development of precautionary policies. Regretfully, genomics and exposomics have developed in silos where methodologies (imputation, stratifications, prediction) theories (e.g. causal inference theories, gene x environment analysis, population dynamics, migrations) and infrastructures have not intersected. They can be seen as the two sides of the One-Health theories where human evolution (and the etiology of chronic and infectious diseases) and the environments have shaped and are still shaping each other over time and evolution. One critical aspect will be to also support longitudinal designs.

However, integrating genome and exposome in medicine brings significant challenges for sciences and technologies. The data is very dense and large. A single person genome is very large (currently more than 40M single nucleotide polymorphisms are included genome-wide analysis), the exposome is possibly larger and with various levels of complexity. We must bring together significant innovation in mathematical and computer science to harness genome-exposome-phenotype associations, and train artificial intelligence (AI) methods. Addressing these challenges shall improve our understanding of disease mechanisms, ultimately leading to more effective strategies for disease prevention and treatment.

The current population samples (e.g. UK biobank, FINNGEN, Estonian Biobank) that are used to train the models for precision medicine are not without bias. There are critical imbalances in terms of for sex, age, gender, ethnicity, poverty, and other factors in the data. To achieve equity in health, and make new

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discoveries, there is an urgent need to continue collecting genomics and exposomics data in large representative samples.

Research needs

To integrate genome and exposome information into medicine, research needs to:

- Focus on harmonization of data collection methodologies for large-scale exposomic x genomics studies, ensuring reproducibility, comparability, and standardization across diverse populations and research frameworks.
  - *Expected impact: This will produce very large libraries with exposomics QTL (quantitative trait loci) to contribute to the exploration of the gene-exposome signal and understand their shared cause on disease susceptibility.*
- Develop high-performance quantum computing to enhance capacity to model non-linear processes with large and complex data.
  - *Expected impact: There is strong evidence that genetic and exposome risk are not fitting the current linear and additive models. Quantum calculation and non-binary systems with support discovery and precision*
- Address privacy, equity and ethical concerns for sharing gene and exposome data in Europe. Developing secure federated frameworks for data protection while promoting collaborative research and personalized healthcare advancements.
  - *Expected impact: Promoting widening and research renewal*
- Ensure equitable access to personalized medicine by reducing disparities in genomic and exposomic research participation, ensuring diverse population representation, and implementing accessible interventions.
- Assess the impact of environmental factors (including psychosocial) on pharmacogenomics and medication efficacy, leading to tailored drug response predictions and improved therapeutic outcomes in line with G4.3.
- Translate molecular signatures of people living in good health and exposure-linked diseases into actionable insights for policymakers, supporting evidence-based regulatory decisions and public health strategies.
- Develop green computing technology to support a green transition in health.

Expected impacts and SDG/Ostrava Declaration relevance

Research on the integration of genomic and exposomic data enhances our understanding of disease etiology, enabling early detection and risk assessment of environmentally influenced diseases such as cancer, neurodevelopmental disorders, and cardiovascular conditions. This aligns with SDG 3 (Good Health and Well-being) and supports the WHO's Global Action Plan for Noncommunicable Diseases (NCDs). Early disease detection and personalized interventions can improve workforce health and productivity, supporting SDG 8 (Decent Work and Economic Growth).

The advancement of fast, cost-effective, and real-time exposure detection technologies (e.g. biosensors, organ-on-chip models, high-throughput screening) supports SDG 9 (Industry, Innovation, and Infrastructure). Moreover, ensuring diverse population representation in exposomic research and improving access to personalized interventions fosters SDG 10 (Reduced Inequalities). This initiative fosters interdisciplinary

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collaboration between scientists, policymakers, and industry leaders, ensuring that exposomic research is translated into impactful global policies (SDG 17).

Finally, the findings contribute to evidence-based policymaking, promoting regulations that reduce exposure to harmful chemicals and environmental pollutants, directly supporting SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) by fostering sustainable, health-conscious policies.

Overall, integrating genomic and exposomic data into medical applications will drive scientific innovation, inform public health strategies, and strengthen global health and environmental policies, aligning with key sustainability and public health goals.

G4.3 Therapeutics: pharmaco-exposomics

Objective

To bring forward the concept of pharmaco-exposomics in order to complement pharmaco-genetics and understand the influence of various environmental factors on drug pharmacokinetics (in particular drug metabolism) and pharmacodynamics (drug safety and response) to improve the benefit/risk of drugs.

Relevance

A substantial proportion of patients do not respond adequately to standard drug treatments or experience adverse drug reactions (ADRs) (1). Improving the prediction of variability in drug response is therefore a key objective for advancing personalised pharmacotherapy.

Pharmacogenetics is increasingly used to optimise drug dosing and identify non-responders in areas such as oncology, cardiology, and psychiatry (2–4). However, drug response is not determined by genetic factors alone. Non-genetic influences—including drug–drug interactions, diet, lifestyle, and environmental exposures—also play a critical role.

Individuals are continuously exposed to a wide range of environmental factors, including chemical mixtures, food-derived compounds, microbiome-related metabolites, and pollutants. Many of these can interact with drug-metabolising enzymes, transporters, and receptors, thereby influencing drug efficacy and safety (5). Despite their importance, these interactions remain poorly characterised due to methodological limitations.

Environmental conditions such as air pollution and extreme heat further influence drug response. Air pollutants (e.g. PM2.5, NO_2, ozone) can exacerbate chronic diseases and interact with medications, while heat exposure can alter physiological responses, increasing the risk of dehydration and adverse drug effects (6–8).

In addition, physiological and pathological factors—including age, sex, pregnancy, nutritional status, and chronic diseases—affect drug metabolism and must be considered alongside environmental exposures. These interacting factors contribute to significant variability in pharmacokinetics and pharmacodynamics across individuals.

Pharmaco-exposomics extends existing approaches such as pharmacogenomics and pharmaco-metabolomics by integrating environmental exposures into the study of drug response. By accounting for both genetic and non-genetic determinants, it offers a more comprehensive framework to understand inter- and intra-individual variability.

Overall, integrating exposome data into pharmacology has the potential to improve treatment selection, enhance therapeutic efficacy, and reduce adverse drug reactions, contributing to more precise and safer healthcare.

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Research needs

The exposome can influence drug actions using several routes (directly or indirectly), hence major gaps remain regarding the influence of exposomics factors such as co-exposure to chemical mixtures, climate change or air pollution, despite already known examples of drug–exposome interactions such as environmental, food, and microbial chemicals on various therapies (5). Key research needs include:

- High-resolution mass spectrometry (HRMS) methodologies will allow researchers to identify the human internal chemical exposome, including co-medication and drug metabolites, and detect prognostic and diagnostic biomarkers (i.e. endogenous metabolites) of drug response in individuals (9) simultaneously. It is possible to have a single platform that measures drugs, their metabolites (including the ones produced by the microbiota), and chemical modifiers of drug metabolism (e.g. enzymatic CYP450 inhibition). Hence one key step will be the establishment of benchmarking workflows and automated data analysis pipeline. While it does not seem realistic to explore the exposome of all individuals undergoing pharmacological therapy, research should focus on identifying the conditions for which an exposome exploration is warranted.
- Extreme heat and air pollution may alter the effectiveness of multiple medications (10). The influence of these external general factors on drug metabolism and responses remains to be studied.
- Medical conditions such as obesity can also be involved in drug metabolism variability. Consequently, obese patients are consuming on average more drugs than non-obese individuals. Research should focus on identifying which diseases or conditions can alter drug metabolism or contaminant metabolism interfering with drug efficacy or disposal.

Expected impacts and policy relevance

Advancing the field of pharmaco-exposomics for personalized pharmacotherapy will:

- Guide clinical decisions based on new evidence related to environmental and (patho)physiological factors and provide recommendations for initial administrations.
- Optimize individual drug responses and minimize ADRs by considering the influence of environmental factors including extreme events
- Educate physicians and all other parties involved in the use and benefits of personalized pharmacotherapy.
- Start the development of workflows and standardization of procedures and development of clinical guidelines for exposomics pre-testing.
- Support the development of recommendations and new regulations for drug development and drug labelling.

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G4.4 Exposome and disease development and progression

Objective

To explain the causal relationships and mechanisms through which the exposome influences disease development and progression, with a focus on key areas such as non-communicable disorders. This research aims to bridge the knowledge gap between environmental exposures and biological processes that lead to pathological outcomes.

To identify key exposome components by characterizing the critical environmental, lifestyle, psychosocial, and biological factors that contribute to the initiation and progression of specific diseases.

To structure these mechanisms in AOPs and to allow identification of various exposures that could trigger adverse outcomes to prevent the development of diseases.

Relevance

The exposome's impact on human health extends beyond single exposures, encompassing cumulative and interactive effects of environmental, chemical, biological, and psychosocial factors. Understanding how these exposures influence disease mechanisms is essential for advancing predictive, preventive, and personalized medicine. For instance:

- *Cancer*: Environmental and lifestyle factors account for the great majority of cancer cases, estimated at 85-90%, while the remaining factors are attributed to hereditary aspects. The interaction between exposomic and (epi)genomic factors also play a critical role. Moreover, socio-economic status and social support are important as the social determinants of health. Identifying the exposome's role in carcinogenesis offers options and approaches for early intervention and potential prevention of several cancer types. The link between the exposome and hallmarks of cancer should be one of these approaches. (1).
- *Occupational diseases*: Exposome analysis can help identify risk factors for occupational diseases, supporting the protection of workers' health.
- *Liver and metabolic diseases*: Exposures to endocrine disruptors, obesogens and metabolic toxins contribute to conditions such as obesity, metabolic fatty liver disease and diabetes. Microbiome disruptions and its interaction with the exposome may also lead to liver and metabolic diseases, potentially through altered gut-liver and gut-brain axes communication and systemic inflammation (2,3).

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- *Neurological and mental disorders*: Psychosocial stressors, neurotoxicants, and diet-related exposures are implicated in mental health and neurodegenerative diseases (4). Emerging evidence highlights the role of gut microbiota imbalances and systemic inflammation in influencing brain function and mental health (5,6). Similarly, there is an emerging link for the nasal microbiome composition and its contribution to the development of Multiple Sclerosis (MS) in patients.

This subgoal highlights critical knowledge gaps that must be understood and then provides a framework for integrating exposome science into medical research, aligning with initiatives like the EU Green Deal, Sustainable Development Goals (SDGs), and Horizon Europe's health priorities for 2030.

Research needs

To understand the role of the exposome in disease development and progression, research needs to:

- Limited understanding of the molecular pathways through which complex and cumulative exposure patterns influence health outcomes.
- Insufficient longitudinal data to establish causation versus correlation for many diseases, and potential levels of individual susceptibility.
- Identification of novel biomarkers for unexplored exposure-disease associations to delineate mechanisms in disease pathways.
- Lack of data on how multiple exposures (chemical, physical, biological, and psychosocial) interact within biological systems over time.
- The field of chemical toxicity is extensively studied, yet significant gaps remain, particularly in understanding the effects of certain chemical families, complex mixtures, and their interactions with other stressors.
- Creating comprehensive, standardized databases that compile global exposure data, including rare and emerging pollutants, to support cross-population studies.
- Limited methodologies exist for accurately measuring and characterizing the (full) spectrum of lifelong environmental exposures, including low-dose and transient exposures.

Expected impact and policy relevance

Impact on health and medicine:

- **Enhanced prevention**: Improved ability to identify high-risk populations and environmental triggers for early intervention and enabling targeted prevention strategies.
- **Therapeutic advances**: Discovery of novel therapeutic targets based on mechanistic understanding of exposure-driven diseases.
- **Precision medicine**: Integration of exposomic data into clinical decision-making for tailored prevention and treatment strategies (integrating the two first items).
- **Economic benefits:** Demonstrating a significant economic impact by reducing healthcare costs through prevention and addressing the root causes of disease.

Policy relevance:

- **Alignment with Green Deal and clean industry Goals**: Addressing environmental health challenges by targeting pollution and exposure mitigation strategies.
- **Sustainable Development Goals (SDGs):** Advancing SDG 3 (Good Health and Well-Being) and SDG 13 (Climate Action) through actionable research findings.
- **EU 2030 perspective**: Supporting Horizon Europe's mission to foster healthier environments and combat major health challenges through interdisciplinary research.

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- **Better informed regulatory frameworks**: Support evidence-based policymaking by providing robust data on harmful exposures and their health impacts, and promoting safer environments.
- **Prioritized, low-cost exposome-informed interventions**: Adapt exposome-informed tools for resource-limited healthcare systems, at low-cost so that a potential scale-up would be supported.

This research will empower policymakers with evidence to design interventions aimed at reducing the burden of exposome-related diseases, thereby advancing public health and sustainability goals.

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G5 Development of methods, tools, infrastructures

Goal 5 of this roadmap focuses on developing advanced measurement tools, integrating health and exposure data, and applying mechanistic and computational frameworks to elucidate exposure-disease relationships. By building human capital, strengthening institutional capacity, and implementing FAIR data infrastructures, this initiative lays the foundation for large-scale, actionable exposome research. These efforts will advance precision prevention, inform public health policy, and drive sustainable solutions for environmental health.

G5.1 Development of analytical tools

Objective

To develop and validate analytical tools for comprehensive measurement of external exposures (air pollutants, diet, noise, chemicals, radiation) and internal markers of exposures (biological responses and disease biomarkers) throughout the human lifespan. These tools should capture exposures at high temporal and spatial resolution, link external and internal signatures, and provide data that can be integrated into epidemiological, regulatory, and medical applications. This includes the development of high-throughput, sensitive, and multi-scale analytical approaches capable of capturing complex mixtures and cumulative exposures over time.

Relevance

Exposome science requires advanced methods that go beyond traditional single-exposure monitoring. New technologies now allow for multi-scale data collection, from real-time wearable sensors to high-throughput molecular profiling. This dual focus—environmental sensing and biological measurement—enables researchers to track how exposures fluctuate during daily life, how they accumulate over years, and how they interact with biological systems.

Such tools are crucial to:

- Enhance environmental and occupational epidemiology by providing reliable and granular exposure data.
- Support communities with actionable information on local exposures.
- Guide regulators in developing standards that better reflect real-world mixture and cumulative exposures.
- Bridge environmental sciences and medicine by linking exposures to biomarkers and disease risk.

Research needs

To support exposome research, development of analytical tools needs to focus on:

- Advancing wearable, miniaturised devices capable of monitoring air pollutants (PM, VOCs), noise, UV, radiation, and temperature with high accuracy over long periods
- Integrating sensors with smartphones and cloud platforms for contextualized exposure mapping (e.g. linking GPS and activity data with peaks in pollution or noise)
- Improving calibration, battery life, and interoperability across sensor platforms; develop algorithms to clean, synchronize, and harmonize multi-sensor data
- Addressing privacy, data security, and participant compliance challenges to ensure reliable and ethical deployment in large cohorts

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- Prioritizing the development of low-cost, ruggedized, and low-maintenance sensors (e.g. for PM2.5, water quality, heat) suitable for deployment in resource-limited, off-grid, and community settings, enabling wider participation and equity in exposome research
- Developing exposure modelling methods to complement sensor data where direct measurement is not feasible
- Using advanced statistical and machine learning approaches (e.g. exposome-wide association studies, causal inference, deep learning) to detect exposure–health associations, identify clusters of exposures, and predict health outcomes.
- Creating simulation datasets, open repositories, and reporting standards to enhance reproducibility and comparability across studies.
- Building harmonized ontologies and common data models for exposure data to facilitate secure data sharing and federation across institutions.
- Expanding high-resolution mass spectrometry and hybrid approaches to characterize known and unknown small molecules, metabolites, and environmental chemicals in biological samples
- Developing workflows to prioritize and interpret unknown features, linking detected compounds back to potential sources and biological pathways
- Improving throughput and reproducibility to achieve large-scale profiling comparable to proteomics or genomics
- Establishing reference standards, quality-control pipelines, and training to ensure results are robust and clinically interpretable
- Complementing mass spectrometry with additional high-throughput technologies, including sequencing-based approaches (e.g. metagenomics) to assess microbiome, epigenetic, and genetic biomarkers
- Creating secure, federated platforms for integrating sensor, modelling, biomarker, and health data, enabling large-scale exposome analyses
- Promoting interdisciplinary training across exposure science, toxicology, molecular biology, bioinformatics, and data science to strengthen expertise in exposome analytics
- Developing cloud-based and federated data infrastructures to enable remote processing of large-scale datasets, ensuring accessibility and scalability
- Supporting community engagement, education, and outreach to facilitate participation from diverse populations and stakeholders, including those unfamiliar with exposome approaches

Expected impacts and SDGs

- **Policy and regulation:** Provide evidence for cumulative and mixture risk assessment, supporting the EU Chemicals Strategy for Sustainability and environmental health directives (SDG 3 – Good Health and Well-being; SDG 12 – Responsible Consumption and Production).
- **Community and environment:** Equip communities and city planners with exposure maps and tools to address disparities, advancing environmental justice (SDG 10 – Reduced Inequalities; SDG 11 – Sustainable Cities and Communities). This includes enabling community-deployable tools and accessible data platforms for local decision-making.

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- **Health systems:** Enable early-warning tools (e.g. sensors detecting acute exposures or biomarker panels indicating chronic risk), laying the foundation for exposome-informed screening and health monitoring.
- **Climate and planetary health:** Track emerging risks from climate change (e.g. wildfire smoke, extreme heat), providing data to inform adaptation and resilience (SDG 13 – Climate Action).
- **Science and innovation:** Create standardized platforms, open repositories, and reproducible workflows, accelerating innovation and collaboration across Europe.

G5.2 Health data linkage: biobanks; electronic health records; cohort data

Objective

To create an integrated FAIR exposome data ecosystem, connecting:

- Environmental exposure data (air, water, food, chemicals, occupational hazards)
- Biomonitoring datasets across Europe
- Health outcomes data for exposure-disease linkage

This will enable population-scale analyses and cross-domain integration to accelerate discovery of exposure–disease relationships and support actionable public health interventions.

Relevance

Many aspects of environmental exposure and health interactions remain fragmented across different research silos. Traditionally, public health, environmental sciences, and biomedical research have operated in isolation, leading to gaps in knowledge and missed opportunities for intervention. Addressing these silos is essential to create a unified, action-oriented exposomics framework.

Specifically, biobanks store biological samples and linked genetic or health data, which, when linked with EHRs, can provide insights into disease mechanisms and treatment responses. Cohort data, collected from long-term population studies, further enriches analyses by tracking health outcomes over time. Integrating biobanks, electronic health records, cohort data, and environmental monitoring systems is essential to link exposome measurements with health outcomes at scale, although current gaps in interoperability, standardized metadata, and secure dataset linkage remain key challenges. The integration and linkage of health data will enable researchers to identify risk factors, improve diagnostics, and develop targeted therapies while ensuring data privacy and ethical considerations.

Moreover, wearable devices and the integration of personalized health data are revolutionizing clinical practices, offering new opportunities to improve patient outcomes. Once confined to clinical settings, affordable technologies can now be deployed outside of hospitals, enabling continuous monitoring of health and environment metrics to improve patient care.

People with chronic diseases can benefit from wearable devices in managing their health, encouraging healthy lifestyle habits and changing daily routines based on environmental information. Wearables such as activity trackers or blood glucose monitoring devices can lead to positive health impacts, including improved physical activity adherence or better disease management. A recent review shows that wearables are currently used in management of many NCDs including diabetes, heart failure, hypertension, (chronic obstructive pulmonary disease, chronic pain, musculoskeletal conditions, and asthma). By integrating existing biobanks and databases with continuous monitoring, personalized recommendations, and participatory research, these technologies embody the promise of a data-driven, exposome-informed future, with far-reaching implications for public health and healthcare policy.

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At the same time, the integration of large-scale health and exposure data must ensure equitable access, robust ethical governance, and context-sensitive implementation, avoiding the risk that standarized data systems overlook local realities or reinforce existing inequalities.

Research needs

The EU should consider developing an exposome data ecosystem adhering to FAIR (Findable, Accessible, Interoperable, Reusable) principles, aligned with the establishment of a large-scale pan-European cohort infrastructure (e.g. a 10 million participant EU cohort). This should include:

- A unified EU-wide exposome database, integrating geospatial, chemical exposure, biomonitoring, and environmental risk data. This should be built on existing efforts within IHEN, European infrastructures (EIRENE, ELIXIR, BBMRI), partnerships (PARC) in collaboration with the European Health Data Space (EHDS). Rather than being duplicative, this database system will increase the utility of this valuable information. Such systems should address current gaps in interoperability and standardized metadata, and enable linkage across environmental, clinical, and socio-economic datasets. This infrastructure should support harmonised data collection, longitudinal follow-up, and repeated biological sampling at population scale, as required for large European cohort initiatives.

- Real-time environmental exposure monitoring systems, leveraging AI, geospatial mapping, and sensor networks to track pollution, occupational hazards, and climate-related risks. Currently, only a limited number of cities have distributed environmental sensor networks. These systems should support both research and real-time public health decision-making. They should also be designed to integrate directly with cohort infrastructures, enabling continuous exposure assessment linked to individual-level health data.

- Cross-border data and sample-sharing agreements to harmonize exposomics research across Europe and ensure compatibility with initiatives like IPCHEM (EU Information Platform for Chemical Monitoring) and the European Health Data Space (EHDS). These agreements are essential to leverage the distinctly EU-level of collaborative science, and can be informed by the experiences of European infrastructures and biobank networks. They should support coordinated governance and harmonisation across Member States, enabling large-scale cohort integration and long-term sustainability of shared infrastructures.

- Development of data management systems to integrate electronic health records (EHRs), exposomics data, and pharmacological databases. Developing such systems requires understanding the needs of existing data and sample repositories and biobanks, like how they can update and upgrade their functions so that the information they hold can become part of the wider exposome research ecosystem. These systems should be interoperable with large-scale cohort platforms, enabling linkage to longitudinal health records, repeated measurements, and real-world evidence generation, including nested trials and intervention studies within cohort populations.

- Establish governance structures (e.g. dedicated committees or expert groups) to define standardized variables for exposome research, coordinate input from research and industry stakeholders, and facilitate integration into existing cohorts and databases. These governance structures should align with large-scale cohort coordination bodies to ensure harmonised protocols, ethical oversight, and strategic alignment across Europe.

- Support long-term national and European strategic initiatives for exposome infrastructure. These include sustained investment in monitoring and biomonitoring systems, systematic data and sample storage, cross-disciplinary training, and locally governed, ethical data management to ensure scalability and long-term impact beyond pilot phases. This should include phased implementation strategies (e.g. pilot cohorts, scale-up phases, and full deployment) consistent with large European cohort initiatives.

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- There is a need to establish a large-scale, pan-European exposome cohort, integrating environmental, biological, clinical, and socio-economic data across the life course. Such a cohort would provide the statistical power and diversity required to understand cumulative exposures, identify vulnerable populations, and support regulatory and public health decision-making at EU level.

G5.3 Data interpretation, causality: linking exposome and toxicological research

Objective

Advance exposome research in Europe by integrating cutting-edge methodologies in toxicology, systems biology, and data science. Specifically, this roadmap aims to foster the use of adverse outcome pathways (AOPs) and new approach methodologies (NAMs) for mechanistic toxicology, while leveraging knowledge extraction tools such as knowledge graphs and artificial intelligence (AI) for data interpretation and integration. The goal is to create a harmonized framework that enhances our understanding of environmental exposures and their impact on human health, including the identification of causal mechanisms and actionable intervention points, by integrating exposome data with experimental toxicology, mechanistic evidence, and advanced causal inference approaches.

Relevance

Exposome research is crucial for deciphering the complex interactions between environmental factors and human biology, which influence disease onset and progression (1,2). The European research landscape has recognized the need for systematic approaches to identify and quantify exposures over the life course. AOPs provide a structured methodology to link molecular initiating events with adverse health outcomes, thereby strengthening causal inference in toxicological assessments (3,4). Concurrently, NAMs offer alternative, high-throughput, and non-animal testing methods that enhance the efficiency and ethical considerations of exposure assessments (5).

Moreover, the extraction and integration of exposome-related knowledge require robust computational tools. Knowledge graphs and AI-powered analytics facilitate the mapping of large-scale, heterogeneous datasets, allowing researchers to discern patterns and establish mechanistic links between exposures and health effects (6,7). These tools are instrumental in synthesizing insights from diverse sources, such as omics data, epidemiological studies, and environmental monitoring (8).

At the same time, caution is needed to avoid overinterpretation of causal relationships, as premature conclusions may lead to scientific uncertainty or policy controversy. Robust validation, transparency, and uncertainty quantification should therefore be integral to exposome-based causal inference.

To accelerate progress in exposome research, this roadmap emphasizes cross-disciplinary collaboration, standardization of data formats, and the development of interoperable platforms. By fostering synergies between toxicological frameworks, data science, and regulatory science, Europe can position itself as a global leader in exposome research, ultimately informing public health policies and precision prevention strategies.

Research needs

Advancing exposome research requires a strong focus on improving data interpretation and causality assessment.

- Integrate high-throughput screening data by leveraging AI-driven models and machine learning techniques to consolidate large-scale exposure and toxicology datasets, enabling improved risk

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assessment and prediction of health outcomes, and strengthening causal inference by integrating epidemiological findings with biological plausibility.

- Further development of AOP frameworks is necessary, incorporating mechanistic insights from omics technologies to strengthen causal inference in chemical exposure assessments.
- The expansion of NAMs is essential to account for the complexity of multiple environmental exposures and their cumulative health effects, including mixture toxicity, low-dose effects, non-linear dose–response relationships, and synergistic or antagonistic interactions across exposure pathways.
- Additionally, the construction of robust, federated knowledge graphs that interlink environmental, biological, and health data will facilitate cross-disciplinary research and discovery.
- Standardization and interoperability are crucial to ensuring common data formats, metadata standards, and open-source platforms that allow for seamless integration and sharing of exposome research findings across different scientific communities.
- Strengthen FAIR data implementation and harmonised fairification approaches to ensure data accessibility, reusability, and equitable sharing across institutions and countries, including the development of user-friendly platforms and training at both early-career and professional levels to support widespread adoption.
- Development of standardized workflows for integrating heterogeneous data to establish clear links between exposome research and toxicological assessments, ensuring consistency and interoperability.
- Advancing human relevance assessment of adverse outcome pathways (AOPs) and associated new approach methodologies (NAMs) to enhance regulatory acceptance and improve risk assessment frameworks.
- Strengthen quantitative models to define thresholds of concern and account for regional variability in exposures, ensuring relevance across different environmental, socio-economic, and geographic contexts.

Europe should support the development of structured training programmes, including doctoral networks and professional education in exposomics, to build long-term capacity across research, healthcare, regulatory, and policy communities.

Expected impacts and SDG/Ostrava Declaration relevance

Exposome research aligns with global sustainability and public health objectives, particularly in the context of the United Nations' Sustainable Development Goals (SDGs) and the Ostrava Declaration on Environment and Health. By identifying key environmental risk factors and their causal links to diseases, exposome research supports the development of more effective public health interventions and disease prevention strategies, contributing to SDG 3 (Good Health and Well-being).

Adoption of AOP and NAM-based methodologies will help reduce reliance on traditional toxicological testing, promoting more ethical and sustainable risk assessment approaches, which align with SDG 12 (Responsible Consumption and Production). Furthermore, enhanced data integration and predictive models will contribute to more informed regulatory decisions, improving environmental health policies at national and EU levels, supporting SDG 13 (Climate Action) and SDG 15 (Life on Land).

Strengthening scientific collaboration, standardization, and innovative methodologies aligns with the Ostrava Declaration's goals to reduce health impacts of environmental exposures and promote evidence-based policymaking. This roadmap provides a foundation for future interdisciplinary research and policy

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developments, ensuring that exposome science contributes meaningfully to sustainable health and environmental solutions.

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G5.4 Implementing exposome approaches: human capital; institutional support; trans-disciplinarity

Objective

Facilitate the implementation of exposome approaches by strengthening human capital, fostering institutional support, and promoting trans-disciplinarity. The goal is to build a sustainable infrastructure that enables the integration of exposome science into public health and regulatory frameworks, ensuring long-term advancements in environmental health research. This requires the development of skilled professionals, dedicated research institutions, and interdisciplinary collaborations that bridge toxicology, epidemiology, data science, and policymaking.

Relevance

Implementing exposome approaches requires a coordinated effort among scientific, institutional, and policy stakeholders. A robust human capital base ensures the continuous development of expertise needed to interpret complex exposome data. Institutional support provides the necessary infrastructure for large-scale exposome projects, while trans-disciplinary collaborations foster innovation and real-world applications.

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The exposome represents a paradigm shift in understanding environmental health, demanding new skills and competencies (1). Strengthening human capital through specialized training programmes, interdisciplinary education, and professional development initiatives will ensure that researchers and practitioners can effectively interpret exposome data (2). This should include early integration of exposome concepts into undergraduate and professional curricula (e.g. medicine, nursing, and public health), as well as continuous training for the existing workforce. Moreover, investment in institutional support is crucial for sustaining exposome research, requiring dedicated funding mechanisms, technological infrastructures, and policy frameworks that encourage long-term engagement with exposome methodologies (3), including capacity building in low- and middle-income countries and historically underrepresented populations.

Trans-disciplinarity is a cornerstone of exposome research, as it necessitates collaboration among various disciplines, including biology, chemistry, medicine, data science, and social sciences (4). Encouraging interdisciplinary partnerships can facilitate the integration of diverse expertise, enhancing the robustness of exposome studies and their applicability in health risk assessment. However, structural barriers remain, as education and training are often siloed across faculties, limiting interaction between health, biomedical, and data science disciplines. Additionally, fostering collaboration between academia, industry, and regulatory agencies can expedite the translation of exposome findings into evidence-based policy measures and public health interventions (5), including closer collaboration with hospitals and clinicians to enrich exposome models with comprehensive clinical data beyond traditional variables.

By addressing these foundational elements, Goal 5.4 aims to create a sustainable ecosystem that drives the integration of exposome science into health policies, ultimately improving disease prevention strategies and public health outcomes in Europe. A well-supported exposome research framework will enable a more comprehensive understanding of environmental exposures and their long-term health effects, contributing to precision prevention and personalized medicine initiatives, while ensuring equitable, globally relevant, and community-informed research.

Research needs

The successful implementation of exposome approaches depends on strengthening human capital, institutional support, and trans-disciplinarity.

- Prioritize the development of human capital as a first step, including the establishment of dedicated training units, interdisciplinary courses, and lifelong learning programmes for both students and the current workforce.
- Research is needed to develop specialized educational programs and training modules that equip professionals with the necessary skills to analyze exposome data, including training in machine learning and artificial intelligence for multi-omics integration and causal discovery in highly heterogeneous datasets.
- Universities and research institutions should establish interdisciplinary curricula that integrate toxicology, epidemiology, computational science, policy analysis, and social sciences, while actively involving community partners and stakeholders in research design and implementation.
- Furthermore, long-term funding strategies must be developed to support infrastructure, enabling sustained collaboration and technological advancements, including support for regional hubs, international partnerships, and equitable North–South collaborations.
- Institutional frameworks should be enhanced to facilitate large-scale exposome research, providing the necessary laboratory, computational, and data-sharing platforms to support investigations across multiple disciplines.

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- Encouraging research networks and centres of excellence will foster continuous innovation, collaboration, and knowledge exchange among experts from diverse backgrounds, including clinicians, social scientists, and community members who bring expertise based on lived experience.

Expected impacts and SDG/Ostrava Declaration relevance

The reinforcement of human capital, institutional capacity, and trans-disciplinary collaboration in exposome research will have significant impacts on public health, environmental policies, and sustainable development. Strengthening the workforce with specialized expertise will enhance the interpretation and application of exposome data, leading to more accurate health risk assessments and disease prevention strategies, directly supporting SDG 3 (Good Health and Well-being). Increased institutional support will drive advancements in exposome infrastructure, fostering long-term research programmes that promote responsible chemical management and sustainable environmental policies, aligning with SDG 12 (Responsible Consumption and Production).

Moreover, trans-disciplinary collaboration will ensure that environmental health challenges are addressed holistically, contributing to SDG 13 (Climate Action) and SDG 15 (Life on Land) by promoting policies that mitigate environmental risks and protect ecosystems. Aligning exposome research efforts with the Ostrava Declaration will strengthen evidence-based policymaking, supporting multi-sectoral cooperation to reduce environmental health risks and improve societal well-being.

By integrating human capital development, institutional investment, and interdisciplinary collaboration into exposome research, this roadmap establishes a sustainable framework that will enable Europe to lead in environmental health sciences. The successful adoption of exposome methodologies will drive public health advancements, facilitate regulatory improvements, and contribute to global sustainability efforts.

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G5.5 Data harmonisation and FAIRification

Objective

Ensure that exposome data is fully FAIRified so that policymakers and other stakeholders can make the most of data which is spread over multiple locations. This will be achieved by continuing to build on existing infrastructure (metadata catalogue, exposome platform and all other contents of the exposome toolbox) which allows researchers to investigate and then use the specific data available in multiple locations for their exposome research. In addition, exposome research is well-integrated in an exposome node of the European Open Science Cloud, EHDS and ESFRI (e.g. ELIXIR, EIRENE, BBMR). This includes the development of community-driven ontologies, standardized variables, and federated data architectures to enable scalable analyses and translation into public health practice.

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Relevance

Harmonised data made findable and available in the metadata catalogue and other tools allows multi-centre and multi-dimensional exposome research to be carried out. Currently data and tools are fragmented across multiple locations worldwide. Interoperable data can be reused time and time again. However, significant challenges remain due to heterogeneous databases, variable definitions, and reporting systems across health and exposome datasets, as well as limited availability of granular, individual-level exposure data.

Coordinated investment in infrastructure, workforce training, and cross-disciplinary collaboration is required to address these gaps and enable robust, scalable, and policy-relevant exposome research.

Research needs

Strengthening exposome data systems requires coordinated efforts to improve standardization, accessibility, and integration:

- Ensure all exposome data sources export harmonized metadata and data dictionaries (e.g. DCAT exposome extensions), supported by common formats, vocabularies, ontologies, quality metrics, and minimal variable sets to enable interoperability, comparability, and reuse across studies and regions
- Develop automated, user-friendly data access procedures and federated or distributed infrastructures that enable secure data storage, exchange, and analysis, while protecting privacy and preventing data breaches
- Establish standard APIs and workflows for data access, linkage, and multi-centre analysis, supporting automation and large-scale, cross-cohort exposome studies
- Ensure exposome tools, platforms, and resources are easily discoverable and well-documented, and support community-based systems to collaboratively maintain and update standards, vocabularies, and ontologies in a transparent and version-controlled way
- Promote integration of diverse environmental and health datasets and strengthen cross-regional collaboration to support cumulative exposure assessment and global comparability

Expected impacts and SDG/Ostrava Declaration relevance

Strengthening FAIR and interoperable exposome data systems will enable large-scale, cross-cohort analyses, improve causal inference, and accelerate the translation of research findings into public health and clinical practice.

This work will directly support EU data and health policy frameworks by enabling secure, harmonised data access and integration across Member States. In particular, it will contribute to the implementation of the European Health Data Space (EHDS), the European Open Science Cloud (EOSC), and ESFRI research infrastructures (e.g. ELIXIR, BBMRI, EIRENE), enabling secure, cross-border data use, facilitating evidence-based decision-making and regulatory coordination, and strengthening Europe’s leadership in data-driven health research and innovation.

Improved data harmonisation will also strengthen regulatory processes by providing more robust and comparable evidence for risk assessment, monitoring, and evaluation of environmental and health policies, including those under the European Green Deal and the Zero Pollution Action Plan.

At the global level, this work aligns with the WHO Ostrava Declaration by supporting better use of environmental and health data for policy action, and contributes to SDG 3 (Good Health and Well-being) and SDG 9 (Industry, Innovation and Infrastructure) through enhanced data-driven innovation and health system performance.

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Overall, FAIRified exposome data will support more transparent, efficient, and evidence-based policies, enabling timely responses to emerging environmental health risks.

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Conclusion and strategic priorities for Europe

Building on the six strategic goals outlined in this roadmap, a clear set of cross-cutting priorities emerges. Together, these define the conditions required for exposome research to deliver tangible impact for health, policy, and innovation in Europe.

1. Move from fragmented to integrated approaches to health

A central message of this roadmap is the need to move beyond siloed approaches to health, environment, and policy. Exposome science provides a unifying framework to integrate chemical, physical, biological, and social exposures across the life course.

Key need:
Develop and implement integrated, life-course approaches to exposure assessment, risk analysis, and health policy that reflect real-world complexity and cumulative effects.

2. Embed the exposome into EU policy and regulatory frameworks

To fully realize its value, exposome science must be systematically embedded into European policy and regulatory processes.

Key need:
Translate exposome knowledge into operational tools for:

- risk assessment (including mixtures and cumulative exposures)
- burden of disease estimation
- urban, environmental, and occupational policies
- prevention and health promotion strategies

This requires stronger science–policy interfaces and closer collaboration between research, regulatory agencies, and policymakers.

3. Ensure that green and societal transitions are health-positive and equitable

Major transitions (energy, mobility, food, circular economy) will reshape the exposome in profound ways. While they offer clear benefits, they also introduce new risks and may exacerbate inequalities if not properly managed.

Key need:
Systematically assess the health impacts of transitions using exposome approaches, ensuring that policies:

- maximise co-benefits for health
- anticipate unintended consequences
- address distributional impacts and inequalities

4. Integrate exposome approaches into healthcare and prevention

The exposome offers major opportunities to transform healthcare, particularly through precision prevention and improved understanding of disease development and treatment response.

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Key need:
Scale up the integration of exposome data into:

- prevention strategies (primary, secondary, tertiary)
- clinical decision-making
- pharmacology and treatment optimisation

This must be supported by investment in training, digital tools, and health system capacity.

5. Build a European exposome data and infrastructure ecosystem

Robust, interoperable data systems are essential to enable large-scale, actionable exposome research.

Key need:
Develop a FAIR, secure, and federated European exposome data ecosystem that:

- links environmental, health, and socio-economic data
- enables cross-border research and policy use
- integrates with initiatives such as EHDS, EOSC, and ESFRI infrastructures

6. Strengthen capacity, skills, and transdisciplinary collaboration

Delivering on the exposome vision requires a new generation of scientists, professionals, and institutions capable of working across disciplines.

Key need:
Invest in:

- interdisciplinary training programmes and doctoral networks
- collaboration between natural sciences, social sciences, and policy
- long-term institutional support for exposome research and implementation

7. Engage citizens and society

Exposome research is inherently linked to people's environments and daily lives. Its success depends on public understanding, trust, and participation.

Key need:
Promote:

- citizen science and participatory approaches
- improved communication and health literacy
- inclusive governance of data and research priorities

8. Position Europe as a global leader in exposome science

Europe has already established a strong foundation through major initiatives and infrastructures. The next step is to consolidate and scale these efforts.

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Key need:
Establish a **long-term European Human Exposome Initiative**, bringing together:

- research and innovation
- infrastructures and data systems
- policy and regulatory integration

This initiative would position Europe at the forefront of global efforts to address the environmental determinants of health.

9. Transform exposome science into European economic and industrial strength

Europe's leadership in exposome research represents not only a scientific achievement but a strategic industrial asset. World-class expertise in biological and digital biomarkers, sensor technologies, AI-driven health analytics, and FAIR data infrastructures positions European actors to compete—and lead—in rapidly growing global markets for precision health, environmental monitoring, and data-driven medicine. Realising this potential requires a deliberate shift from research excellence to market translation.

Key need: Establish structured mechanisms to convert exposome innovation into economic value, including:

- **Public-private partnership frameworks** bringing together research institutions, pharma, MedTech, environmental monitoring companies, and digital health industry to co-develop and commercialize exposome-derived products and services
- **European exposome technology platforms** scaling biological and digital biomarkers, sensor systems, and AI health tools for export to global markets
- **Innovation pipelines** connecting academic outputs to SMEs, start-ups, and established industry actors through dedicated funding instruments, regulatory sandboxes, and technology transfer programmes
- **Positioning European standards and methods** — developed through IHEN and related initiatives — as international reference frameworks, creating first-mover advantages in emerging regulatory and commercial markets

This industrial dimension is not secondary to the public health mission: it is the mechanism that sustains long-term investment, generates return on public R&D expenditure, and ensures that European exposome infrastructure remains competitive, self-reinforcing, and globally influential. Embedding this competitiveness logic into the European Human Exposome Initiative from the outset will be critical to its durability and impact.

Final message

The exposome represents a paradigm shift in how we understand and act on health. It moves the focus from isolated risk factors to the complex, cumulative, and unequal exposures that shape health across the life course.

Delivering on this vision requires coordinated action across research, policy, healthcare, private sector and society. By investing in the exposome now, Europe can:

- improve population health and reduce inequalities
- strengthen prevention and healthcare systems
- support sustainable and health-promoting transitions
- enhance competitiveness and innovation

This roadmap provides the foundation. The next step is implementation.

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- ISGlobal - Barcelona Institute for Global Health
- UU - Utrecht University
- MU- Masaryk University
- Inserm - French National Institute of Health and Medical Research
- UMCG - University Medical Center Groningen
- IARC - The International Agency for Research on Cancer – WHO
- CUT - Cyprus University of Technology
- Oulu - University of Oulu
- HEAL - Health and Environment Alliance
- ANSES - French Agency for Food, Environmental and Occupational Health & Safety
- HERA - Health Environment Response Agency
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