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The European exposure science strategy 2020–2030

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ABSTRACT

Exposure science is an emerging and rapidly growing field dedicated to all aspects concerning the contact between chemical, biological, physical or psycho-social stressors and human and ecological receptors. With that, exposure science plays a central role in protecting human and ecosystem health, and contributes to the global transition towards a green and sustainable society. In Europe, however, exposure science is currently not sufficiently recognised as a scientific field, resulting in inefficient uptake into policies. In response, the wider European exposure science community developed elements and actions under the auspices of the Europe Regional Chapter of the International Society of Exposure Science (ISES Europe), for identified priority areas, namely education, exposure models, exposure data, human biomonitoring, and policy uptake. In the present document, we synthesize these strategic elements into an overarching 'European Exposure Science Strategy 2020–2030', following three strategic objectives that focus on acknowledging exposure science as an independent and interconnected field, harmonizing approaches and tools across regulations, and exploring collaboration, education and funding mechanisms. To operationalise this strategy, we present concrete key actions and propose initiatives and funding options for advancing the underlying science, cultivating broader education and cross-sector exposure knowledge transfer, and fostering effective uptake of exposure information into policy. We aim at anchoring European efforts in the global exposure science context, with a special focus on the interface between scientific advancements, application in decision support, and dissemination and training. This will help to develop exposure science as a strong scientific field with the ultimate goal to successfully assess and manage various stressors across sectors and geographic scales.

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1. Exposure science as key to protecting human and ecosystem health

1.1. Towards sustainable global societies

The United Nations adopted the Sustainable Development Goals (SDGs) in 2015, aiming to serve as a blueprint to achieve a better and more sustainable future for all by 2030 (UN, 2017), with ambitious reduction targets for exposure to chemical, biological, physical and psycho-social stressors worldwide. In Europe, translating such targets into actionable efforts that consider the specific infrastructural, socio-economic and environmental conditions has led to the European Green Deal (EC, 2019a). This policy initiative has set out a vision for Europe to become a sustainable, climate-neutral and circular economy by 2050, and to better protect humans and biodiversity as part of an ambitious approach to tackle pollution from all sources and move towards a toxic-free environment. Various strategies support this vision, including a 'Towards Zero Pollution for Air, Water and Soil' Action Plan, a strategic framework on 'Health and Safety at Work', a 'Proposal for a Revision of the Industrial Emissions Directive', a 'Beating Cancer' Plan, and the 'Chemicals Strategy for Sustainability' (EC, 2021a, c; EC 2022a, b; EC 2020b). These strategies identify pollution as a key driver for amplifying planetary crises (Kosnik et al., 2022a; Persson et al., 2022), and emphasise the importance of exposure to harmful chemicals and other stressors as a local-to-global threat for human health and ecosystem quality (Brack et al., 2022; Fantke and Illner, 2019). These strategies also highlight that existing EU chemicals policies need to respond more rapidly and more effectively to the challenges posed by exposure to various stressors, to develop and deploy sustainable chemistries, materials and products that enable a green and digital transition of our economy and society (EC, 2020b; Fantke et al., 2021b). This includes ensuring that all chemicals and materials are designed, manufactured and (re-)used in a way that they are 'safe and sustainable-by-design' (SSbD), promoting that exposure to substances and other stressors of concern are minimised and their use substituted as far as possible.

As outlined in the following sections, current challenges need to be overcome in different priority areas of exposure science to successfully support the ambitions across these European strategies. This includes challenges for exposure modelling, exposure data production and analytics, human biomonitoring, uptake of exposure knowledge into policy, education and training of exposure knowledge, and funding and international collaboration to establish exposure science as a scientific field. To align efforts to address the various challenges, an overarching and actionable strategy for advancing exposure science is required, considering European boundary conditions.

1.2. A role for exposure science

With its focus on the contact between stressors and receptors, including sources, pathways and processes, exposure science faces increasing pressure due to a growing interaction of chemical and product life cycles with the wider natural and built environment, leading to a wide range of unwanted effects on human health and the wider earth support system, including ecosystem quality. With that, there are increasing requirements for systemically advancing and strengthening exposure science and its contribution to risk and health impact assessment and designing a sustainable and circular economy, in support of a healthy society and environment.

A strategic analysis focused on how chemicals are regulated in Europe and how chemical safety is currently defined, funded and enforced in Europe, being mainly hazard (or toxicity) driven (Bruinen de Bruin et al., 2019). This mechanism hampers effective investments and innovation, such as the development of accepted non-animal testing methods. To overcome these specific challenges and position exposure science as an enabler for protecting human and ecosystem health, it is key to embed exposure science into the various relevant strategic research and innovation schemes as well as into future policy cycles (Fig. 1). With that, exposure science will be a central element in measuring progress toward achieving zero pollution ambitions, boosting green technologies, materials, decent work and innovative business models, and be applied holistically across chemicals legislation as a stepping stone towards safe, secure and sustainable transitions.

Needs to strengthen the role of exposure science are seen in the ambitions laid out in the European Green Deal and in the global sustainable development agenda, and require innovations in the way we assess and manage exposure and related risks. Exposure science is, however, currently not adequately recognised in the scientific community and by regulators, since it is a relatively young scientific field that is still working on broadly-agreed data, problem definition, analysis and improved methods and standards for exposure assessment (Sheldon and Hubal, 2009; Lioy, 2015; Fantke et al., 2020b). Moreover, exposure reduction measures are often important and, in some cases, even the only means to effectively reduce risks (Sheldon et al., 2008), which can hamper improving impact prevention, (early) detection and monitoring of human and planetary health. Consequently, the remediation of the historical imbalance between hazard and exposure is an emerging public and environmental health priority. Therefore, efforts should primarily focus on (i) advancing exposure science by bolstering this rapidly developing field, and (ii) taking up exposure science as an integral part of regulatory risk and health impact assessment and management frameworks. To successfully address these challenges, an overarching strategy for exposure science is urgently needed.

To fully establish exposure science as a mature scientific field that provides ready-to-apply data and methods that inform relevant policy frameworks, advances across different priority areas are needed. Such advances need to be based on a clear and operational implementation plan over the next decade, to strengthen and increase the application of exposure science, including allocating resources, establishing funding possibilities, and developing performance tracking indicators.

The unique, complex regulatory landscape and the numerous ambitious policy strategies in Europe create a specific system of conditions and requirements that have a direct impact on developing and applying exposure science. These include the transition towards a more coherent and stronger regulatory framework, an established educational frame specific to the field, and enhanced competitiveness of the European chemical industry and other sectors and their value chains. Such conditions and requirements are anchored in important ambitions of the current policy agenda, along with a demand for digitalizing industry, establishing a strong biomonitoring network, and promoting novel and cleaner industrial processes and technologies through, for example, SSbD chemicals, materials and products (EC, 2020b). While general data and modelling approaches are independent of regions, parameterisation of exposure models for specific settings is not. Hence, a strategy for exposure science that should support European ambitions must be tailored to meet Europe's specific set of conditions and requirements, while at the same time interacting with global exposure science advancements and applications.

Initiated in 2017, we present here the finalized 'European Exposure Science Strategy 2020 – 2030' that was guided by the Europe Regional Chapter of the International Society of Exposure Science (ISES Europe) in a multi-year process through targeted discussions, implementing strategic workshops and establishing dedicated working groups focusing on different priority areas for exposure science, involving public and private stakeholders from academia, industry, small and medium enterprises (SME), European authorities and European Member State agencies, insurance associations, and non-government organisations. The overall strategy-building process is summarized in Fig. 2. As a result of this process, we describe in the present document the overall strategy. This includes the overall vision and action plan for advancing exposure science and application in Europe based on synthesising the key actions across five priority areas (Bruinen de Bruin et al., 2022; Connolly et al., 2022; Kosnik et al., 2022b; Schlüter et al., 2022; Zare Jeddi et al., 2022)

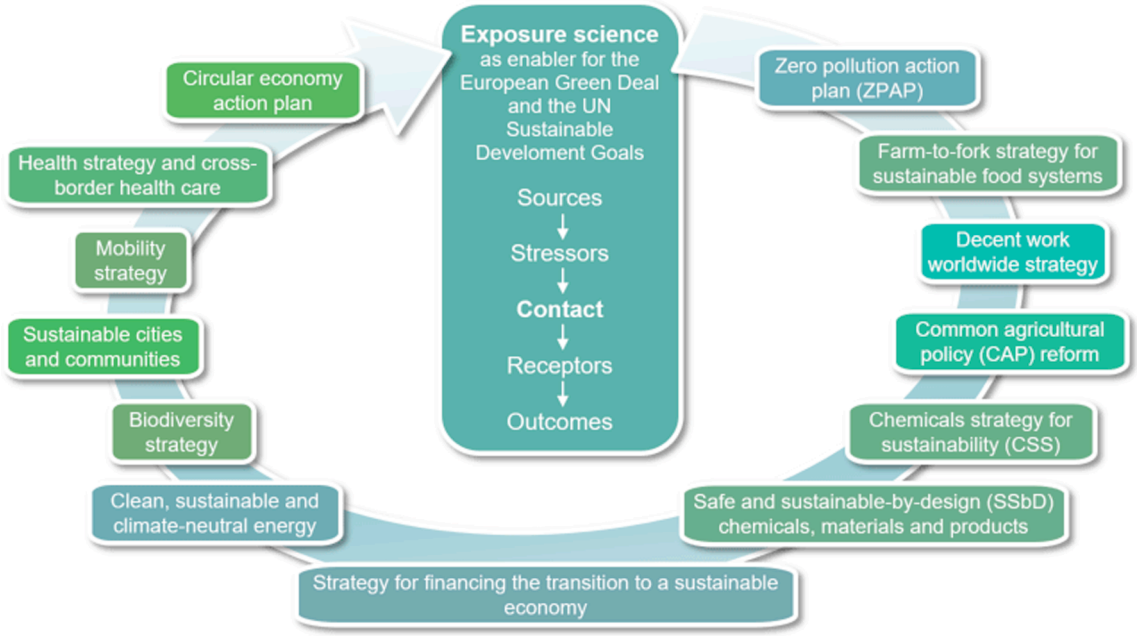

Fig. 1. Exposure science (centre block) as an enabler for protecting human and ecosystem health across the wider range of European strategies and facilitating a global sustainability transition (surrounding elements).

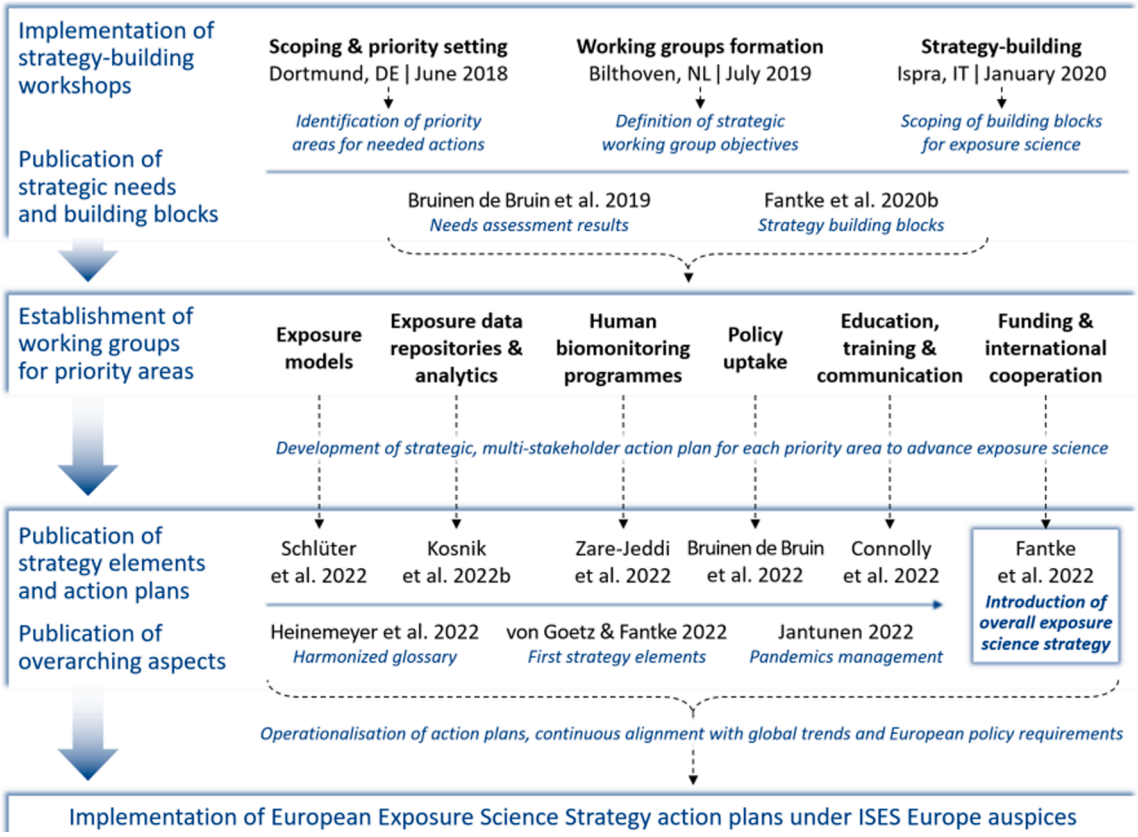

Fig. 2. Main elements in the development of the European Exposure Science Strategy 2020–2030 from scoping to implementation, with six overarching priority areas for advancing exposure science. The overall strategy is introduced in the present article (Fantke et al., 2022). Cited references are found in the references list at the end of the present document.

as summarized in von Goetz and Fantke (2022). Building on these, the overall strategy furthermore contains an outline of potential funding mechanisms and the role of international cooperation for the wider adoption of our strategy elements, aligned with global efforts and policy frameworks, as an overarching sixth priority area.

2. Priority areas to stimulate progress in exposure science and application

Exposure science is not only a multi-faceted, emerging field, but also captures various levels of complexity and integration at the chemicals-health-environment nexus. Thus, exposure science is strongly connected to research ambitions and industrial innovations through its highly interdisciplinary and systems-level perspective, which is an essential ingredient for addressing our complex societal challenges, from reducing chemical pollution to managing associated human burden of disease and environmental impacts.

Exposure science requires advancements in research, including the generation of data and development of concepts and modelling tools, application by policy, industry and other stakeholders in decision support frameworks, as well as dissemination and training through education programmes. Research, application and education are closely interlinked, with specific challenges in each of them. ISES Europe initiated a series of stakeholder workshops held at European public institutions (2018: BAuA Federal Institute for Occupational Safety and Health, Germany; 2019: RIVM National Institute for Public Health and the Environment, The Netherlands; 2020: EC-JRC European Commission – Joint Research Centre, Italy) and established dedicated working groups to identify and characterize key challenges for advancing and operationalizing exposure science in Europe, and to discuss possible ways forward to overcome these challenges within a 10-year timeframe (Fantke et al., 2020b). Through this process, six priority areas for advancing exposure science and its application through targeted actions have been defined, considering the specific regulatory and capacity-building conditions in Europe.

Systematically educating and training practitioners across sectors and different levels of detail is crucial for a consistent application of exposure knowledge. This includes, for example, experts and practitioners to provide input for risk and impact assessment to companies, authorities and other decision makers. The 1st priority area for exposure science, therefore, focuses on improving and extending *education, training and communication*. The main ambition is to create a new generation of exposure science experts that have an in-depth exposure science knowledge, including developing and applying appropriate tools, to contribute and have an impact on policy and decision-making in the real world. This requires developing exposure science education and training that yields credible, well-defined career pathways for exposure scientists. As an initial step, the framework for developing a dedicated exposure science curriculum is proposed, and harmonised learning outcomes are identified. This will feed into training exposure science graduates, as well as promoting awareness and recognition of exposure science as an independent field in the academic world (Connolly et al., 2022).

From simple data-driven tools and mathematical relationships to complex computational algorithms, exposure models are an essential element of almost all decision-support frameworks relevant for exposure science (Bonnell et al., 2018). To address the various existing challenges and gaps in modelling exposure, the 2nd priority area for exposure science is the advancement and integration of *exposure models*. As an overarching aim, it is essential to improve the methodology and acknowledgement of exposure modelling as a viable decision-support instrument. This can be achieved by advancing and integrating existing models and tools, developing new methods and support for understudied research fields, improving user guidance, and understanding regulatory needs for exposure modelling. As initial actions, building a model inventory, informing about training options, ensuring continuous model development, evaluating available exposure models, and developing a best-practices handbook for exposure modeling were identified (Schlüter et al., 2022).

Collecting, storing and analysing high-quality exposure data is the backbone of any exposure assessment, regardless of its application context (Fantke et al., 2020a). In support of enhancing and harmonizing data storage, processing and analysis, the 3rd priority area for exposure science is the advancement, digitalisation and technical operationalisation of *exposure data repositories and analytics*. As an overall goal, strategic guidance needs to be provided for an integrated European exposure data production and management framework for use in science and policy, which builds on current and future data analysis and digitalisation trends. Achieving this goal requires to develop a consistent exposure data terminology, to increase data curation capacity and transparency, availability and ownership accountability, to readily trace data use over and across different scientific domains and policy areas, to enhance data storage and related infrastructure, to increase automation in data management and data integration, and to advance data analysis methods (Aurisano and Fantke, 2022; Kosnik et al., 2022b).

Special emphasis is put on evaluating actual exposures among populations as well as exposure estimates against measured exposure data produced throughout European biomonitoring networks. This will partly build on citizen science approaches, with related results serving also as benchmarks of current exposure distributions. To generate reliable information on exposure distributions for the general population as well as for vulnerable population groups, the 4th priority area for exposure science is, therefore, the systematic implementation of both large-scale and more focused *human biomonitoring programmes*. With a focus on providing a holistic view on human exposure to substances including their metabolites, human biomonitoring provides insights on bioavailability and (de-)activation of chemicals integrated over time and covering different exposure routes, which may further improve risk and health impact assessments. Thus, more and high-quality biomonitoring data will present an effective solution to tackle new challenges, and can contribute to the transformation of regulatory risk assessment, management of chemicals and Europe's zero pollution strategy. However, for concrete regulatory use and uptake of biomonitoring data, their quality needs to be improved by further optimisation, harmonisation, quality assurance/quality control, as well as clear regulatory guidance on all steps of the assessment process from study design to reporting (Zare Jeddi et al., 2022). Important steps towards more harmonisation across Europe have been achieved during the EU Horizon 2020 European human biomonitoring initiative, HBM4EU (Ganzleben et al., 2017). Following up and extending the scope of HBM4EU beyond human biomonitoring, the 7-year 'European Partnership for the Assessment of Risks from Chemicals' (PARC, https://www.anses.fr/en/content/european-partnership-assessment-risks-chemicals-parc) builds on existing methods and data to more broadly consolidate and advance risk assessment. However, the fields of non-environmental source monitoring, exposure factor identification and exposure modelling, which are closely linked to human biomonitoring, are underrepresented in PARC and will hence require parallel efforts.

The extent to which exposure data and methods can be included in policy frameworks is driven by our ability to meet the requirements for applying exposure science in practice and its uptake into regulations. The 5th identified priority area for exposure science is, therefore, to improve the effectiveness and efficiency of *policy uptake*. This is mainly achieved through the development and implementation of a common scientific exposure assessment framework, supported by baseline acceptance criteria and a shared knowledge base enhancing exchangeability and acceptability of exposure knowledge within and across relevant EU policies. To enable the use of such a common framework in support of improving regulatory risk management practices and increasing stakeholder acceptance, exposure science innovation needs to be more effectively included along the policy-making cycle as well as become an integral part of company decision-support systems (Bruinen de Bruin et al., 2022).

Finally, strategic efforts are required to define actions within and across these five priority areas for exposure science, but also to coordinate investment programmes across public and private institutions in Europe and align defined actions with national and international exposure science priorities outside Europe. Hence, the 6th and last

priority area for exposure science is to establish a sustainable policy frame for the systematic implementation of exposure science, including *funding and international cooperation*. While targeted working groups have developed exposure science strategy elements in dedicated publications, the cross-cutting priority area focusing on funding and international collaboration will be described in more detail in the present document. One specific example that requires international cooperation is to develop a globally harmonized and accepted exposure science terminology, which facilitates an efficient and consistent uptake of exposure information across regulatory and other decision support frameworks. To aid in the development of such a standardised terminology, the ISES Europe glossary of aligned exposure science terms is intended to serve as a starting point that should lead to a broader discussion on terminology among exposure scientists worldwide and across regulatory and methodological silos (Heinemeyer et al., 2022). More generally, appropriate funding mechanisms need to be established to facilitate such harmonisation and other exposure science-related efforts, thriving for the development of baseline criteria that can be holistically applied across current and future policies that require exposure information. This can be achieved through a combination of (a) integrating exposure science elements into existing public and private funding schemes, (b) initializing policy discussion or recommendation documents (so-called 'aide-mémoire') that are used to aid policy makers in defining new or adjusting existing funding programmes, and (c) generating funding specifically targeting more fundamental exposure science aspects, such as mixture assessment with aggregate and combined exposure modelling, biomonitoring, assessing specific high-priority chemical classes and (types of) uses, or applying digitalisation and big-data methods in exposure predictions. Each of these targeted exposure science aspects, however, will have to be mapped to regulatory frameworks in Europe vs. outside Europe in order to identify differences in the applicability of proposed data and methods in specific regulatory contexts and an efficient distribution of underlying scientific efforts to generate and readily share appropriate and relevant exposure information. This will determine suitable funding mechanisms inside and outside Europe along with coordinated cooperation.

3. A European action plan for exposure science-to-regulation

3.1. Vision, strategic objectives and concrete actions

Our vision is that exposure science is used in prevention, intervention, regulation and other decision-making processes to advance a safe, secure, sustainable and healthy society and is fully acknowledged as a scientific field in Europe and worldwide (Fantke et al., 2020b). This vision builds on the overarching ambition to foster the consistent and systematic uptake of exposure science in Europe across regulatory and non-regulatory frameworks as well as by the various relevant stakeholders. Three defined strategic objectives (SO) address key requirements to achieve this ambition:

- SO1: To define and have acknowledgement of exposure science as an independent and interconnected field, and to establish an identity for exposure scientists.
- SO2: To organize, standardize and harmonize terminologies, data, methods and tools across regulations and research areas in Europe within and linked to exposure assessment and risk management practices worldwide.
- SO3: To establish a long-term dialogue across research areas, and identify resources, education and funding needs and mechanisms for advancing exposure science.

The strategic objectives will be achieved by proposing an action plan of key actions across the six defined priority areas for advancing exposure science. These key actions, along with their relation to the three strategic objectives, their integration into the global exposure science context, and proposed operational timelines for each action are summarized in Fig. 3.

3.2. Strategy implementation progress tracking and perspectives

To implement the different key actions defined in Fig. 3 as part of the European exposure science strategy, relevant targets and progress indicators will be defined. Such indicators include the implementation of exposure data, methods and models in regulatory and other assessment and management frameworks in Europe, the establishment and certification of new courses with a focus on or containing central elements of exposure science, the implementation of initiatives for the harmonisation and consensus-building of exposure science data and methods, such as the human biomonitoring global registry framework (Zare Jeddi et al., 2021) and the UNEP GLAM exposure assessment framework (Fantke et al., 2021a), as well as the change in exposure science-related expenditure and intensity of funding invested in research and development (R&D). Measuring progress towards achieving such targets according to the timeline proposed in Fig. 4 until 2030 and for the expected scope requires the definition of relevant key performance indicators (KPI). Examples of such a KPI could be related to the number of newly established exposure science courses, the number of additional, concrete exposure data, models and tools that are taken up into relevant policy strategies, the fraction of arbitrarily defined exposure-related aspects that has been replaced by scientific data and methods in regulatory and other assessment frameworks, and how much exposure science has effectively been incorporated into regulatory guidelines and compliances processes that have explicitly taken up exposure metrics and data. While such KPI will be meaningful for measuring progress towards policy uptake of exposure science, other metrics will be needed to measure underlying scientific innovation and advances, where progress cannot be measured solely based on the number of new data and models generated, but also includes scientific consensus and wide scientific application and evaluation of generated exposure knowledge.

Based on a set of relevant indicators for progress measurement, exposure science will be effectively advanced in terms of both the underlying science and the uptake into policy and other decision-making frameworks. However, additional recommendations will help to enable a sustainable growth of exposure science into a strong and recognized field in Europe and beyond. These recommendations include: stronger synergies between exposure science and other research areas to grow as interdisciplinary scientific field, increasing the awareness of exposure science as an independent scientific field, higher emphasis on funding exposure science through different excellence, innovation and other private and public, targeted funding mechanisms, the improvement of education and training of exposure scientists, strengthening of exposure science R&D activities in all sectors, the implementation and relevance of FAIR data principles in exposure science R&D to support the better integration of digitalisation techniques into exposure science, a stronger connection between exposure science and European strategic goals around public and environmental health, sustainability and a green transition for Europe's economy, to anchor exposure science in other international strategies, and proposing efforts in support of maturing the field and creating a global community of practice. Finally, a stronger involvement of stakeholders for implementing the European exposure science strategy elements as well as for advancing and promoting exposure science in Europe and elsewhere is crucial, to better understand what actions need to be jointly brought forward across exposure science aspects and how to facilitate more efficient uptake into policy and other frameworks. Overall, the implementation of the proposed strategy and its progress measurement require efforts that go well beyond the current resources within ISES Europe working groups.

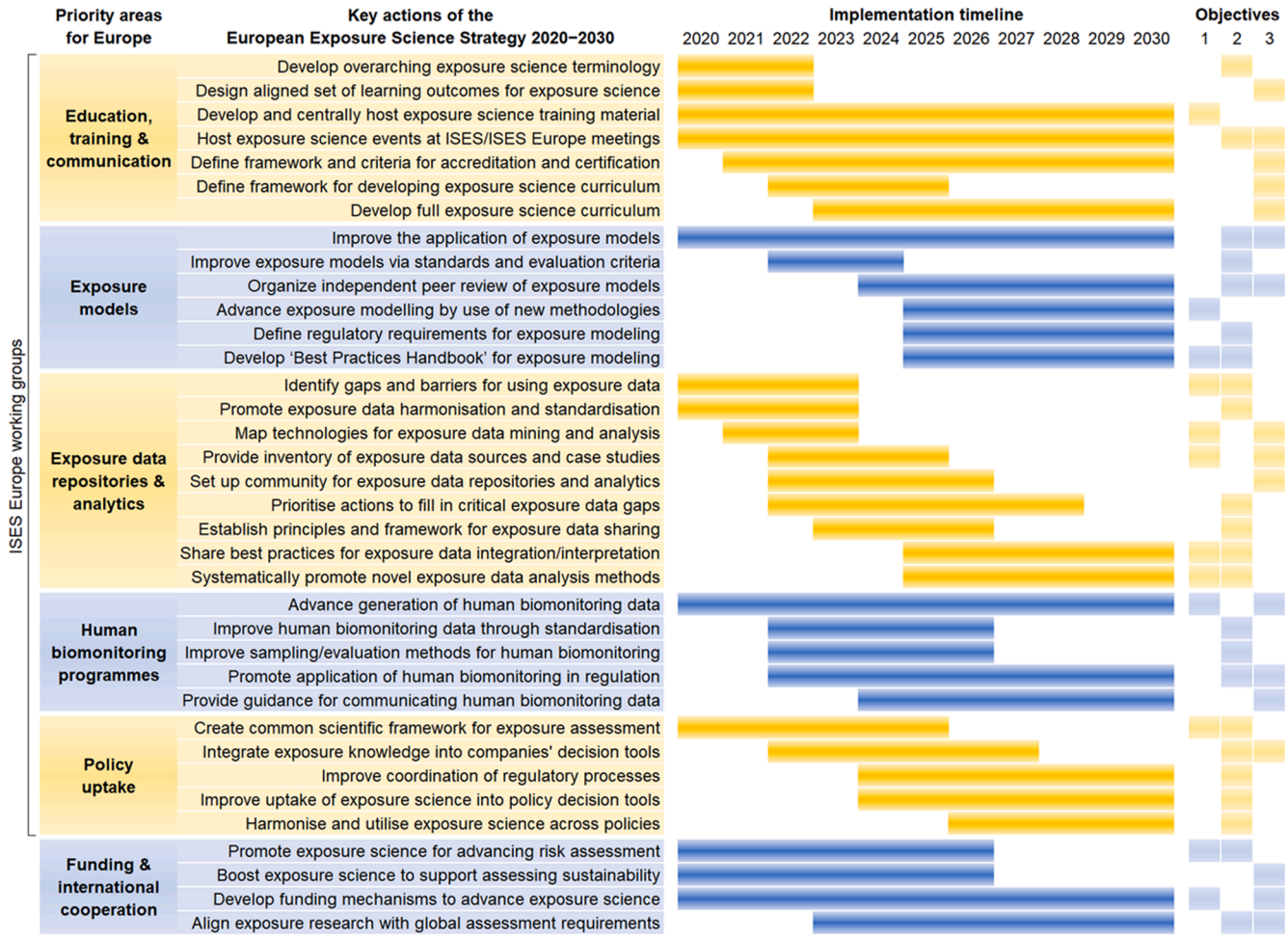

Fig. 3. Overall plan of key actions of the European Exposure Science Strategy 2020–2030, their timelines and contributions to the three strategic objectives for advancing exposure science in Europe across priority areas. For additional details, see the underlying strategy document for each priority area, i.e. education (Connolly et al., 2022), exposure models (Schlüter et al., 2022), exposure data (Kosnik et al., 2022b), human biomonitoring (Zare Jeddi et al., 2022), and policy uptake (Bruinen de Bruin et al., 2022), while actions beyond the current ISES Europe working groups' efforts related to international funding and cooperation as sixth priority area are detailed in the present article (Fantke et al., 2022).

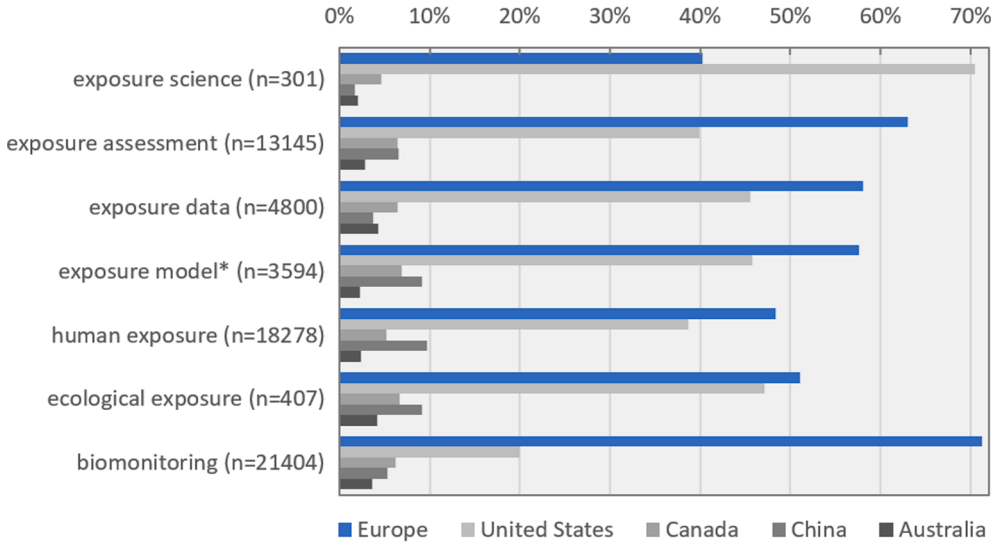

Fig. 4. Contribution to exposure-related publications listed in Scopus (https://scopus.com) for search strings associated with exposure science. 'Europe' includes EU27 as of 2021, plus UK, Switzerland and Norway.

4. Scaling it up: The role of international cooperation

Europe is just one of several global regions with respect to exposure science, including the US with their well-established exposure research programmes and the Global South, where many of the highest exposures occur. Especially in the context of global supply chains, human mobility and health hazards (e.g. pandemics, transboundary pollution, and global biodiversity loss), European strategic advances in exposure science can hopefully serve as a role model for other regions, but also need to be integrated into and aligned with global-level efforts. Such a global context of European actions is particularly relevant for aspects around broadly accepted and harmonised standards for exposure data and models. Moreover, an integration of European exposure advances into global actions will be crucial to facilitate coordinated actions to close fundamental exposure knowledge gaps, to build worldwide biomonitoring programmes and data sharing platforms, and to foster more effective uptake of exposure information and assessment approaches into global policy frameworks, all of which require broader international consensus-building and standardisation processes. An overview of how the proposed key actions across the six priority areas for Europe can be integrated into the wider exposure science context is provided in Table 1.

Global efforts relevant for advancing exposure science are typically led by global-level organisations, including the Organisation for Economic Co-operation and Development (OECD, through the Working Party on Exposure Assessment, WPEA), UN Environment (e.g. through its SAICM programme), or the World Health Organisation (WHO, e.g. through its International Programme on Chemical Safety, IPCS), as well as by global-level scientific networks and societies, including the International Society of Exposure Science (ISES) or the International Commission on Occupational Health (ICOH). These global-level organisations would also be responsible for establishing mechanisms to coordinate exposure-related questions and efforts of international or global relevance, such as responding consistently and rapidly to pollution outbreaks and pandemics, based on proposing, for example, a suitable set of effective exposure reduction measures (Deziel et al., 2020; Jantunen, 2022).

In parallel and in addition to various EU calls (e.g. Marie Skłodowska-Curie Actions under Horizon Europe) also open to researchers from countries outside Europe, bilateral agreements between the European Commission or its individual EU Member States and other nations facilitate a broader cooperation across exposure scientists around the world. Such agreements exist as European Research Council (ERC) Implementing Agreements with 10 non-European countries, including for example an agreement with the US via its National Science Foundation (NSF), established in 2012 and renewed in 2019, with 32 cooperative projects implemented or ongoing that received a total NSF funding of €10.6 million, (https://nsf.gov), and as Cooperation Agreements on Science and Technology with 20 non-European countries, including for example an agreement with the key partner country China, established in 1999 and renewed in 2019, with nearly 1800 EU-based research projects that involved researchers from China according to CORDIS (https://cordis.europea.eu) (EC, 2019b).

Bilateral national-level agreements complement EU-level cooperation initiatives and exist between numerous European and non-European countries, including for example a Research Collaboration Agreement between the Innovation Fund Denmark (IFD) and the Brazil Research Fund, the São Paulo Research Foundation (FAPESP), established in 2011 and renewed in 2019, with 24 research grants/scholarships implemented or ongoing (https://bv.fapesp.br/en/133). Finally, international and global public–private partnerships (PPP) can create a long-term knowledge exchange culture across sectors, guiding strategic investment. A PPP example is the Life Cycle Initiative (https://www.lifecycleinitiative.org) hosted at UN Environment, to foster the global use of credible life cycle knowledge to support decisions and policies towards the shared vision of sustainability as a public good. Similar initiatives

Table 1
Overview of the possible integration into the wider exposure science context for each of the key actions across exposure science priority areas for Europe. For details around the key actions for each priority area see the listed references.

Key actions	Integration into the wider exposure science context
1st priority area: Education, training and communication (Connolly et al., 2022)	
Develop an overarching exposure science terminology	Develop a live and broadly accessible document that will include international input to feed into a global consensus-building process for a consistent exposure science terminology
Design an aligned set of learning outcomes for exposure science	Provide a starting point for defining and agreeing on a set of learning outcomes for exposure science, tailored to European and other regions' specific requirements
Develop and centrally host exposure science training material	Develop global awareness and recognition of exposure science as an independent field through the production of exposure science material (e.g. information on exposure science courses)
Host exposure science events at ISES/ISES Europe meetings	Adopt different strategies to enhance communication for promoting dialogue among exposure scientists within Europe and worldwide
Define the framework for developing exposure science curriculum	Draw on and align with conditions of existing curricula around exposure science in Europe and other regions
Develop a full exposure science curriculum	Feed into the development and advancement of international exposure science education and training programmes
Define the framework and criteria for accreditation and certification	Define and tailor criteria towards specific conditions of different regions as part of a global accreditation and certification process for exposure science
2nd priority area: Exposure models (Schlüter et al., 2022)	
Improve application of exposure models	Improve training and accessibility of exposure model information in Europe and elsewhere
Improve exposure models via standards and evaluation criteria	Advance internationally accepted model evaluation and generation of measurement data for model development and evaluation
Organize independent peer review of exposure models	Boost international acceptance of exposure models through alignment of model-review standards
Advance exposure modelling by use of new methodologies	Enhance dialogue by meetings as a mix of scientific conference and dedicated workshops at European level
Define regulatory requirements for exposure modelling	Agreement on a European platform and actively managed process to arrive at a commonly accepted set of exposure models
Develop 'Best Practices Handbook' for exposure modelling	Provide an internationally recognised reference document for best practices promotion in exposure modelling
3rd priority area: Exposure data repositories and analytics (Kosnik et al., 2022b)	
Identify gaps and barriers for using exposure data	Align with requirements in policy and industry for exposure data storage and analysis
Promote exposure data harmonisation and standardisation	Increase interoperability of exposure-related data through international standards for application across regulations, sectors, and regions
Map technologies for exposure data mining and analysis	Enhance usability of new methods and technologies for applying exposure data to policy and other decision support frameworks across regions
Provide inventory of exposure data sources and case studies	Increase availability and uptake of exposure data by policy makers, companies and other stakeholder
Set up community for exposure data repositories and analytics	Facilitate dialogue and broader dissemination of exposure data collection, storage and analysis across scientists and practitioners in Europe and worldwide
Prioritise actions to fill in critical exposure data gaps	Boost the usefulness and reliability of exposure data for use in regulatory and other decision support tools

(*continued on next page*)

Table 1 (*continued*)

Key actions	Integration into the wider exposure science context
Establish principles and framework for exposure data sharing	Boost international acceptance and sharing of exposure data through alignment of data ownership and interoperability
Share best practices for data integration/interpretation	Provide an internationally recognised reference for best practices promotion in exposure data integration methods and interpretation
Systematically promote novel exposure data analysis methods	Increase trust and innovation potential for advanced exposure data analysis methods and technologies
4th priority area: Human biomonitoring programmes (Zare Jeddi et al., 2022)	
Advance generation of human biomonitoring data	Feed into a global pool of continuously generated and reported human biomonitoring data for application in different regulatory and other decision-support contexts
Improve human biomonitoring data through standardisation	Increase comparability and interoperability of human biomonitoring data through international standards for application across regulations, sectors, and regions
Improve sampling/evaluation methods for human biomonitoring	Improve the reliability and applicability of human biomonitoring data for use in regulatory and other decision support tools
Promote application of human biomonitoring in regulation	Increase the effective uptake of existing and newly generated human biomonitoring data into policy
Provide guidance for communicating human biomonitoring data	Boost the structural integration of human biomonitoring data in regulatory and other decision-support contexts by supporting interpretation and stakeholder acceptance
5th priority area: Policy uptake (Bruinen de Bruin et al., 2022)	
Create common scientific framework for exposure assessment	Define the starting point for globally applicable scientific foundation of regulatory exposure assessment across national and international policy frameworks
Integrate exposure knowledge into companies' decision tools	Promote uptake of exposure knowledge into global supply chain management strategies
Improve coordination of regulatory processes	Feed into workflows of European and international policy frameworks relevant for exposure science
Improve uptake of exposure science into policy decision tools	Contribute to streamlined interface of exposure science output and policy requirements at national, European and international levels
Harmonise and utilise exposure science across policies	Provide a starting point for harmonized integration of exposure knowledge across health and safety, security and sustainability policies and strategies
6th priority area: Funding and international cooperation*	
Promote exposure science for advancing risk assessment	Define exposure science as a solution provider for protecting human and ecosystem health
Boost exposure science to support assessing sustainability	Develop indicators using exposure science as stepping stone for measuring global transitions towards SSbD chemicals and materials, climate neutrality and sustainable use of natural resources
Develop funding mechanisms to advance exposure science	Establish global long-term programmes to continuously advancing and providing education and training in the field of exposure science in Europe and link to different international funding programmes
Align exposure research with global assessment requirements	Facilitate effective integration and alignment of European exposure research with global research and policy-implementation programmes (e.g. under UNEP, OECD)

* No dedicated ISES Europe working group was yet established for funding and international cooperation; this priority area is discussed in more detail in the present study.

could boost exposure knowledge as solution providers to combat pollution and overcome human and ecosystem health challenges worldwide. In addition, European and non-European associations will be an important driver to integrate exposure science into their respective focal and geographic context, such as the Institution of Occupational Safety and Health (https://iosh.com) in Europe or the American Conference of Governmental Industrial Hygienists (https://acgih.org) in the U.S.

All these mechanisms foster international cooperation beyond collaboration within Europe to anchor exposure science in ongoing and future international strategies in support of jointly overcoming complex barriers towards a sustainable future, with our 'European Exposure Science Strategy 2020–2030' as an important and integral building block.

5. Funding for strategy implementation

5.1. Investment in research, development and innovation

While the challenges, needs and actions for the exposure science priority areas on education, exposure models, exposure data, human biomonitoring, and policy uptake are extensively discussed elsewhere (Bruinen de Bruin et al., 2022; Connolly et al., 2022; Kosnik et al., 2022b; Schlüter et al., 2022; Zare Jeddi et al., 2022), aspects related to relevant funding mechanisms to advance exposure science are detailed in the following.

Considering the potential of exposure science to help address some of the most urgent societal challenges, from chemical pollution to human health damages and biodiversity loss, related public and private investment in exposure research and development (R&D) activities as key driver of innovation is steadily increasing. According to Eurostat figures (https://ec.europa.eu/eurostat), EU Member States have spent more than €300 billion in R&D in 2019, which equals an R&D intensity of 2.2% of EU's GDP that is relatively stable over the last years, yet lower than the EU ambition of 3%. This R&D funding is largely spent on engineering and technology (65%) and natural sciences (18%), with only less than 10% spent on medical and health sciences.

The private sector invested worldwide more than €900 billion in R&D in 2019, with ITC (23% contribution) and health industries (20.5%) as dominating sectors (the influence of the COVID-19 pandemic is not yet reflected in these figures) (EC, 2020a). Although the private sector in Europe contributes with the largest share to overall R&D investment, with an annual investment growth rate of 5.6%, Europe lags well behind as compared to the US (10.8%) and China (21%).

Although the contribution of R&D funding of exposure science cannot be accurately estimated, a large share is likely attributable to investment in the healthcare sector. However, within this sector, the highest investment is rather spent on disease treatment than on disease prevention, of which the latter is more directly related to exposure science. Other sectors with relevant R&D funding that are related to exposure science are, for example, biotechnology and nanotechnology development, which also aim at reducing exposure associated with conventional technologies, although most of the R&D investment in these sectors is not directly related to exposure research. While it is difficult to compare Europe with other regions for R&D investment, there is a clear trend that Europe is already becoming a major player in the field of exposure science. This is demonstrated by the fact that authors with European affiliations contributed to ~ 60 % of worldwide exposure-related publications listed in Scopus until end of 2021 (https://scopus.com; weighted average over search strings that include 'exposure' and 'science' or 'assessment' or 'data' or 'model*' or 'human' or 'ecological' as well as 'biomonitoring', see Fig. 4). The only other region that dominates exposure science related publications is currently the US, while other regions fall far behind Europe. However, R&D investment within Europe varies widely from an R&D intensity of 0.5% in Romania to 3.5% in Belgium and Sweden in 2020 as a percentage of

GDP, requiring further balancing.

5.2. Existing global funding programmes

At the global level, several programmes and initiatives exist that are relevant in terms of funding exposure research, either directly or as part of other science fields. This includes funding support from, amongst others, the United Nations Environment Programme (UN Environment), the Global Alliance on Health and Pollution (GAHP), the World Health Organization (WHO), the World Business Council for Sustainable Development (WBCSD), and the International Association of National Public Health Institutes (IANPHI). A specific example is the Global Environment Facility (GEF), which funds projects in support of the SDGs, including biodiversity, hazardous chemicals, and food security. GEF has funded more than 5200 projects in 164 countries through a total GEF grant volume of €17 billion and related co-funding of €110 billion (https://thegef.org/country), and works with 18 international agencies, such as the International Union for Conservation of Nature (IUCN), the Food and Agriculture Organization (FAO), and UN Environment. GEF recently funded a €25 million project (of which ~70% is beneficiary co-funding) on 'Global Best Practices on Emerging Chemical Policy Issues of Concern under the Strategic Approach to International Chemicals Management (SAICM)', which advances science and policy implementation of, for example, assessing exposure and risk of chemicals in consumer products in collaboration with researchers from Europe (Aurisano et al., 2021; Huang et al., 2022). However, although exposure science plays a role in certain sub-components of this GEF project and in projects funded by other above-listed and similar organisations, global-level public funding programmes or initiatives that focus specifically on advancing exposure science are lacking.

Another possibility for global funding relevant for exposure research are private foundations. The Global Burden of Disease (GBD), for example, is a comprehensive, global research programme assessing the morbidity and mortality from exposure to 87 environmental, behavioural and other risk factors in 204 countries (https://ghdx.healthdata.org), in a collaborative effort of more than 3600 researchers from 145 countries, including almost all European countries (Murray et al., 2020). The GBD study was originally institutionalised at the WHO back in 1990, and is now led by the Institute for Health Metrics and Evaluation and funded by the private Bill and Melinda Gates Foundation, who spent €45 billion since 2000 in support of GBD and several other national and international research programmes. While GBD research focuses mostly on the link between risk factors and health outcomes, little focus is put on exposure research. Another example of private funding are industry associations, such as the International Council of Chemical Associations (ICCA, https://icca-chem.org), which invested €44 billion in R&D in 2017. However, the largest share is spent on chemicals and process design and development, while little is invested in exposure research (Oxford Economics, 2019).

5.3. Existing funding programmes in Europe

In November 2020, the European Parliament and EU Member States agreed on the largest public EU-financed funding package ever, consisting of a long-term budget for 2021–2027 of €1.07 trillion and the temporary recovery instrument NextGenerationEU of €750 billion (EC, 2020d). More than 75% of this EU budget are managed in partnership with national and regional authorities, largely through five big 'Structural & Investment Funds', while the rest is more or less directly managed by the EU. One third of upcoming funding will be used to finance the European Green Deal to improve the well-being and health of citizens and future generations as part of providing a path to achieving the SDGs, while fostering economic growth and competitiveness of the European private sector.

The European Green Deal is a central element in Horizon Europe, the EU's flagship programme for funding R&D with a total budget of nearly €96 billion, where it fosters various aspects that are tightly related to exposure science. These include, for example, specific calls to tackle combined exposure and mixture toxicity of chemicals, reduction and mitigation of persistent and mobile chemicals in the environment, or relating to the exposome concept, and establishing the PARC partnership, of which the latter is being funded through a single project with a financial contribution of €200 million from the EU and an expected co-funding of beneficiaries of at least 50% (EC, 2020c). Although exposure research is still targeted only to a very limited extent, these and similar currently ongoing and upcoming calls will be an important driver to advance exposure science innovation, with application in Europe and beyond, including Horizon Europe calls around SSbD approaches.

In addition to EU-wide public funding programmes, national funding will play an important role, with priorities in many Member States and other European countries that are well-aligned with the overall ambition for a green transition in Europe and, hence, with relevance for exposure science. Examples of related national-level funding mechanisms include programmes from independent national research and science foundations, environmental protection agencies, and environmental ministries.

In parallel to public funding, Europe also offers investment programmes through European and national industry and trade associations, foundations, societies, non-governmental associations, and other initiatives. An example is the 'Long-Range Research Initiative of the European Chemical Industry Council' (Cefic-LRI, https://cefic-lri.org), which was initiated to respond to public and stakeholder concerns and to close gaps in industry knowledge critical to risk assessment. This initiative—also supporting projects beyond Europe—supports research that addresses priority areas of the chemical industry regarding human and ecosystem health impacts of chemicals, including understanding everyday exposures to chemicals. Another example is the scientific and non-profit 'European Centre for Ecotoxicology and Toxicology of Chemicals' (ECETOC, https://ecetoc.org), which promotes research for enhancing the effectiveness and efficiency of chemicals risk assessment—with exposure science as one of the central focus areas.

5.4. Towards sustainable funding of exposure science in the future

Overall, European and global initiatives offer a plethora of funding opportunities to support innovation in exposure science and its uptake into policy. However, while in the US programmes specifically funding exposure science related research (e.g. exposure biology and the exposome, see https://niehs.nih.gov/research/supported/exposure) have been developed since the publication of the National Research Council report on 'Exposure Science in the 21st Century' (NRC, 2012), there are rarely any dedicated programmes that specifically target exposure science advancements in Europe or at the global scale, beyond e.g. the European Human Exposome Network (EHEN, https://humanexposome.eu). Instead, exposure science is required as a complement and will have to be integrated in funding of other, better established areas.

To foster the implementation of more targeted exposure science funding as part of the European exposure science strategy, it is important to increase the acceptance of exposure science as an acknowledged and relevant solutions provider for advancing risk assessment, to boost exposure science as a tool to support measuring progress towards global environmental sustainability, to develop strategic funding mechanisms that focus on advancing specific exposure science aspects, and to align exposure research with requirements for exposure knowledge across regulatory and non-regulatory assessment and management frameworks. In this context, it is important to emphasise the relevance of exposure science to support the Green Deal and to collaborate with related investors, funding agencies and national banks, in particular by exploring the role of exposure science to support sustainable financing efforts, and to strengthen the development of related regulations and standards, such as in the context of a proposed Corporate Sustainability Reporting Directive (EC, 2021b) and related reporting standards.

6. The way forward

There is momentum for exposure science in Europe. ISES Europe, its working groups targeting different priority areas, and the wider European exposure science community have already taken the first steps towards lifting the field and creating an overarching strategy for the years to come. While the overall strategy is presented here, along with recommendations for fostering exposure science through funding and international collaboration, detailed strategy elements can be found for the different priority areas in dedicated publications. For a successful implementation of the strategy's key actions, we recommend that ISES Europe continues to take a leading role, complemented with targeted initiatives and funding for advancing the underlying science, cultivating broader education and cross-sector exposure knowledge transfer, fostering effective uptake of exposure information into policy and other decision-making frameworks, and anchoring European efforts in the global exposure science context. We further recommend dedicating additional efforts to the interface between scientific advancements (exposure modelling, exposure data repositories and analytics, human biomonitoring, etc.), application by policy, industry and other stakeholders in decision support frameworks, and dissemination and training through a broader set of education programmes. This will help to build exposure science as a strong scientific field that will ultimately be applied to assess and manage exposure to the wider realm of stressors, including exposure to chemicals, but also exposure to plastic pollution, biological stressors and related pandemics such as COVID-19, physical stressors including radiation, heat waves, noise, and psycho-social stress. With that, exposure science will reach its full potential as a key discipline in protecting human and ecosystem health, and facilitating a sustainable transition in Europe and worldwide.

7. Disclaimer

The views and opinions expressed in this article are exclusively those of the authors and do not represent the official position of their respective institutions.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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