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SimpleBox4Planet: environmental fate modelling of PFASs and their alternatives *via* the Enalos Cloud Platform

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This work presents the development of *SimpleBox4Planet*, a user-friendly web application implementation of SimpleBox, and demonstrates its use in facilitating the assessment of the environmental fate of per- and polyfluoroalkyl substances (PFASs) as well as other chemicals of interest, with the aim of supporting research into safer chemical alternatives with lower environmental impact. The *SimpleBox4Planet* web application is freely accessible on the Enalos Cloud Platform (https://www.enaloscloud.novamechanics.com/proplanet/simplebox4planet/ and https://www.enaloscloud.novamechanics.com/chiasma/simplebox4planet/). The *SimpleBox4Planet* web application integrates the SimpleBox (version 4.04) multimedia mass balance model (based on a 'Mackay type' model), accommodating both steady-state (level III) and quasi-dynamic (level IV) computations of mass flows and chemical concentrations across three environmental scales: regional, continental and global, while also considering the chemical distributions at each scale across environmental compartments, including air, soil, water and sediment, thus streamlining the workflow and enhancing visualisation of the model outcomes. The complexities related to modelling SimpleBox through MS Excel spreadsheets are eliminated through the design of the user-friendly graphical user interface (GUI) provided by *SimpleBox4Planet*. This interface enables users to input the physicochemical properties of any chemical of interest (based on its CAS number) from the CompTox Chemicals Dashboard either directly or dynamically through application programming interfaces (APIs), to define emission rates, and to configure landscape settings. Both expert and non-expert users can efficiently perform complex multimedia fate modelling, significantly broadening the tool's applicability in regulatory, academic, and industrial contexts. Furthermore, the platform facilitates integration with other tools and models, including Life Cycle Impact Assessment (LCIA) frameworks, and can be used as an input to risk assessment, to support the evaluation of both ecotoxicological and human health impacts.

Sustainability spotlight

This work supports sustainability by providing an accessible computational tool to model how persistent chemicals like PFASs move and accumulate in the environment. Delivered as a web-based platform, *SimpleBox4Planet* reduces the need for resource-intensive laboratory testing and complex manual modeling, saving time and limiting environmental sampling. It enables the identification of safer chemical alternatives, supporting responsible consumption and production (SDG 12) and protecting human and environmental health (SDG 3). By being freely available and interoperable with other assessment tools, it fosters innovation and infrastructure for environmental protection (SDG 9). Through evaluating legacy PFASs and greener substitutes, *SimpleBox4Planet* informs sustainable policies and encourages the design of safer, sustainable-by-design materials.

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1 Introduction

Understanding the fate and transport of chemicals across multiple environmental scales is essential for evaluating their ecotoxicological risks and potential impacts on human health. Evaluating the environmental persistence of chemicals requires a comprehensive understanding of their transport and fate, including far from their emission sources over long distances in air, water, soil and sediment media. Additionally, a crucial consideration is the dispersion of these chemicals across distinct geographic scales, including regional, continental and global domains, which is essential for effectively assessing potential risks to ecosystems and human health. In response to these challenges, several multimedia environmental models have been developed,[1] classified into 3 categories: fugacity-based compartmental models, integrated spatial-multimedia compartmental models (ISMCM) and linked spatial single-media models (LSSMM). These three categories differ in the treatment of spatial and temporal resolution, as well as in their respective complexity levels.[2,3] Among these models, the SimpleBox model, a fugacity based multimedia mass balance model, is often used to model non-ionizable organics, ionizable organics and metals across regional, continental and global scales.[4–8] On the regional and continental scales, SimpleBox consists of nine well-mixed homogeneous compartments including air, three soil compartments (natural, agricultural and other soil), three water compartments (freshwater, freshwater lakes and coastal seawater) and two sediment/vegetation compartments (fresh water sediment and coastal marine sediment). The global scale is further classified into three zones, moderate, arctic and tropical, each consisting of five well-mixed homogeneous compartments including air, soil, two water compartments (surface and deep ocean water) and ocean sediment.[5]

The SimpleBox model (version 4.04) employs the level III ‘Mackay type’ model for steady-state modelling, where the mass in each compartment remains constant with time, and the level IV ‘Mackay type’ model for non-steady-state modelling, allowing the mass in each compartment to vary with time. However, unlike the fugacity-based approach adopted by Mackay and coworkers,[9–11] the mass flows and concentrations of chemicals in the SimpleBox model are calculated using concentration-based ‘piston velocity’ type mass transfer coefficients ($m\ s^{-1}$) rather than fugacity-based ‘conductivity’ type coefficients.[6,12] The widespread acceptance of the SimpleBox model is highlighted by its integration into the risk policy tool ‘Chesar’ of the European Union, hosted by the European Chemicals Agency.[5] The model is employed to demonstrate that chemicals can be managed safely, ensuring compliance with the EU's stringent Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) regulations by verifying that environmental impacts remain within acceptable limits defined by REACH.[4,5] The SimpleBox model is also integrated within Life Cycle Impact Assessment models, such as the UseTox model,[13] for modelling the fate of chemicals. While fugacity-based models like SimpleBox are widely favored due to their simplicity and ease of execution, they do suffer from limitations. Specifically, the accuracy and reliability of calculations rely on the quality and precision of input parameters, such as physicochemical properties and transformation rates in soil, air, surface and/or sediments. Also, the assumption of the uniform mixing of chemicals in the compartment becomes invalid when modelling the fate of chemicals quantitatively at smaller scales or in heterogeneous environments.[1] Nonetheless, the SimpleBox model remains a powerful and practical approach for evaluating chemical safety, supporting informed environmental risk assessments, and facilitating regulatory compliance.

The objective of this work is to present the development of *SimpleBox4Planet*, a free-to-use web application that integrates the SimpleBox model (version 4.04) for performing both steady-state and dynamic (non-steady-state) simulations. The motivation behind developing *SimpleBox4Planet* is to provide a user-friendly interface that simplifies the execution of the SimpleBox model by removing the complexities of running simulations through Excel spreadsheets and making it accessible to users regardless of their technical and programming expertise. Additionally, *SimpleBox4Planet* includes Application Programming Interfaces (APIs) to facilitate integration with external software systems and tools, including regulatory and decision-support tools. It also provides users with the ability to dynamically retrieve physicochemical properties by entering a CAS Registry Number from the CompTox Chemicals Dashboard (EPA).[14] Here, we demonstrate the capability of the *SimpleBox4Planet* web application to assess and compare the fate and transport of chemicals, using the family of PFASs and their alternatives, which are designed to be less persistent in the environment, although the web application also enables users to define and evaluate any chemical of interest.

SimpleBox4Planet enables users to either select from predefined cases/scenarios or to customize emission rates across regional, continental and global scales, as well as landscape settings. One of its key features is a comparative tool that allows users to compute the total mass distribution of different chemicals under the same emission and landscape settings,

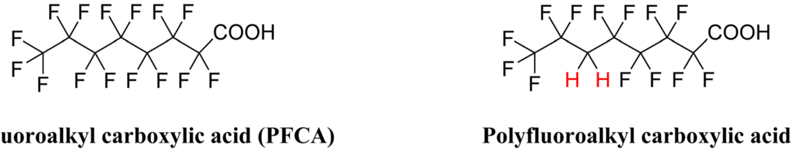


Fig. 1 Structural comparison between a perfluoroalkyl carboxylic acid (PFCA) and a polyfluoroalkyl carboxylic acid. The left panel shows a PFCA, where all hydrogen atoms on the alkyl chain are replaced by fluorine atoms. The right panel illustrates a polyfluoroalkyl carboxylic acid, where some hydrogen atoms remain on the alkyl chain, highlighting the partial fluorination characteristic of polyfluorinated substances.

thus providing valuable insights into which substances pose the least environmental threat. This is particularly relevant for per- and polyfluoroalkyl substances (PFASs), a diverse class of synthetic organofluorine compounds, with an estimated inventory exceeding 4000 individual substances.[15] The European Commission (EC) has declared PFASs as emerging organic contaminants due to their environmental persistence and potential risks to human health and ecosystems.[16–18] All PFASs share a similar molecular architecture – a hydrophobic fully fluorinated (perfluorinated) or partially fluorinated (polyfluorinated) carbon backbone paired with a hydrophilic functional headgroup, resulting in unique amphiphilic properties.[18] An example illustrating the structural distinction between polyfluorinated and perfluorinated carboxylic acid substances is shown in Fig. 1, where the left panel depicts a perfluoroalkyl carboxylic acid (PFCA) with all hydrogen atoms on the alkyl chain replaced by fluorine atoms, and the right panel shows a polyfluoroalkyl carboxylic acid, in which some hydrogen atoms still remain on the alkyl chain. Regulatory agencies worldwide have expressed growing concern over long-chain perfluoroalkyl sulfonic acids (PFSAs) with more than six carbon-fluorine bonds and long-chain perfluorocarboxylic acids (PFCAs) containing more than seven carbon–fluorine bonds, due to their greater potential for bioaccumulation compared to their short-chain counterparts.[19,20] Among these substances, perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) are the most extensively studied and frequently cited in scientific research.[16,17,21] Their short-chain alternatives include perfluorohexanoic acid (PFHxA) and perfluorobutane sulfonic acid (PFBS).[15] The chemical structure of PFASs underpins their extreme thermodynamic and kinetic stability, conferred by the strength of the carbon–fluorine bond, which has a bond energy of 466 kJ mol^{-1},[22] rendering them resistant to abiotic degradation processes (*e.g.*, hydrolysis, photolysis, and oxidation) and biotic degradation pathways (*e.g.*, microbial metabolism and enzymatic transformation).[23,24] This has led to their classification as 'forever chemicals'.[25,26]

Due to their outstanding resistance to heat and chemical breakdown, combined with their unique surfactant properties, PFASs have been extensively used in waterproof textiles, grease-resistant food packaging, non-stick cookware, semiconductor manufacturing and fire suppression systems.[23,27] Their incorporation into textiles, paper-based packaging, electronics, and aqueous film-forming foams (AFFFs) is particularly favored due to their unique hydrophobic and oleophobic surface-modifying characteristics.[17,28–30] However, their resistance to degradation, combined with their ability to partition between air, water, soil, and sediment, along with the atmospheric transport and oxidative transformation of volatile PFAS precursors, enhances their environmental mobility and facilitates their long-range atmospheric transport, enabling their deposition in and contamination of remote regions far from the primary emission sources.[18,31–36] Epidemiological and toxicological evidence links PFAS exposure to hepatic toxicity, immune system dysregulation, endocrine disruption, and carcinogenicity,[37,38] highlighting the critical need for comprehensive environmental monitoring and multimedia fate modelling to quantify the fate and transport of PFASs and assess their long-term impacts on ecosystems and human populations.[15,27,39]

Releases of PFASs originate from primary emissions, which represent direct emissions from industrial chemical manufacturing facilities, and secondary emissions, which represent indirect sources of emissions resulting from the environmental transformation of precursor compounds and the remobilization from contaminated environmental reservoirs.[23] Primary emissions include direct sources of PFAS emissions such as fluoropolymer manufacturing facilities, electrochemical fluorination (ECF) plants, telomerization production sites, aqueous film-forming foam (AFFF) applications at firefighting training grounds, textile finishing plants, paper mills, semiconductor manufacturing operations, wastewater treatment plants (WWTPs) and landfills.[18,40] In contrast, secondary emissions refer to indirect PFAS releases that arise through diffuse sources, including emissions from unknown origins, atmospheric transport and deposition of volatile precursors, leaching from PFAS-treated consumer products, and chemical or biological transformation of precursor compounds into stable PFASs.[40–43] Once released into the environment, PFASs partition and distribute across all major environmental compartments, including atmospheric aerosols, the hydrosphere (surface water, groundwater, and seawater), the cryosphere (glacial and permafrost environments), the lithosphere (soils and sediments), and the biosphere (wildlife and human tissues).[35,44]

The partitioning dynamics between air, water, soil and sediment are governed by the unique physicochemical properties of PFASs, which consist of low vapor pressures, variable acid dissociation constants ($\text{p}K_\text{a}$), and a broad spectrum of organic-carbon-based partition coefficient ($\log K_\text{oc}$) values.[44,45] Long-chain PFASs, including perfluoroalkyl carboxylic acids (PFCAs) such as PFOA and perfluoroalkyl sulfonic acids (PFSAs) such as PFOS, preferentially sorb to sediments, suspended particulates, and biotic tissues (biological macromolecules such as proteins and phospholipid membranes), due to their strong hydrophobicity and low vapor pressure, contributing to their bioaccumulation and biomagnification in aquatic and terrestrial organisms.[35,46] In contrast, short-chain PFASs (typically possessing fewer than six perfluorinated carbons), with lower hydrophobicity and weaker adsorption coefficients (K_d), persist predominantly in the aqueous phase, demonstrating enhanced advective transport through surface water and porous media.[47]

While shorter-chain PFASs have been introduced as replacements for long-chain PFASs, recent evidence suggests that their enhanced mobility increases their potential to contaminate groundwater and migrate through porous media, particularly in low organic carbon aquifers.[47] Additionally, the volatilization and atmospheric transport of neutral and ionic PFAS precursors serve as key mechanisms for their global distribution. PFAS precursors, particularly fluorotelomer alcohols (FTOHs) and perfluoroalkyl sulfonamido ethanols (FOSEs), undergo long-range atmospheric transport in the gas phase due to their volatility,[42] followed by oxidative degradation *via* hydroxyl radical attack to yield persistent terminal perfluoroalkyl acids such as PFOA and PFOS,[48] which subsequently undergo atmospheric deposition processes, including precipitation (wet deposition) and aerosol particle adhesion (dry deposition).[42] This differential environmental mobility, controlled by chain length, functional group chemistry, and local geochemical conditions (*e.g.*, ionic strength, pH, and mineral composition), plays a critical role in determining localized *versus* long-range environmental dispersion.[49]

The environmental persistence and health risks associated with PFASs have prompted extensive research into safer alternatives across various industries. A comprehensive study identified 530 PFAS-free alternatives spanning 325 applications in 18 industries, including 162 alternative substances, 163 alternative materials, 128 alternative products, 37 alternative processes, and 40 alternative technologies, whereas for 83 applications of PFASs no alternatives have been identified as yet.[50] For instance, advanced ceramics like silicon nitride and boron nitride have been proposed as replacements for PFASs in high-temperature applications such as cookware and industrial processes, offering thermal stability without releasing harmful substances.[27] Additionally, fluorine-free firefighting foams (F3) are under development to match the efficacy of traditional PFAS-based foams, aiming to reduce environmental contamination from fire suppression activities.[51] Despite these advancements, certain applications, particularly in industrial processes like plastic and rubber production, currently lack suitable PFAS alternatives, underscoring the need for ongoing research and development to address these gaps.[50]

The next sections outline the theory underpinning SimpleBox, present the development of the web application interface, provide an example of the practical application of the *SimpleBox4Planet* web application *via* a case study focusing on the environmental fate and transport of perfluorooctanoic acid (PFOA), a well-characterized and extensively studied PFAS known for its environmental persistence and mobility,[17,40,44,52,53] and provide some future perspectives for further development of *SimpleBox4Planet* to enhance its integration into regulatory risk assessment and life cycle assessment approaches.

2 Methods and materials

2.1 SimpleBox model

The *SimpleBox4Planet* web application integrates the SimpleBox model (version 4.04), a nested multimedia environmental fate model, designed to simulate the transport and distribution of chemical substances across multiple homogeneous environmental compartments (represented by boxes) at different spatial scales.[5] The model operates at regional, continental, and global scales, incorporating reversible mass transport processes between scales, highlighting the dynamic exchange of chemicals at these levels, as shown in Fig. 2. Within the global scale, three distinct climatic zones are defined: the arctic, moderate, and tropic zones, allowing for a refined representation of geographical variations in environmental fate processes.[4,5]

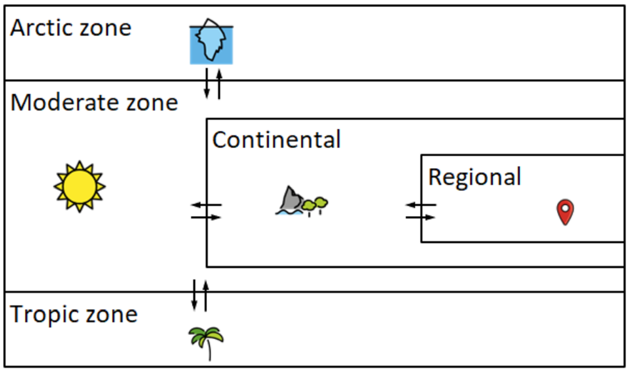


Fig. 2 Schematic representation of the SimpleBox 4.04 model structure, illustrating the nested environmental fate modelling approach at three spatial scales: regional, continental, and global. The global scale is further divided into three climatic zones – arctic, moderate, and tropic.

At both the local (regional) and continental scales, SimpleBox 4.04 defines nine homogeneous environmental compartments to capture the behavior of chemicals in different environmental compartments. These include the atmospheric compartment (air), three soil compartments (natural soil, agricultural soil, and other soil), three aquatic compartments (freshwater, freshwater lakes, and coastal seawater) and two sediment compartments (freshwater sediment and coastal marine sediment). Fig. 3 illustrates the interconnected nature of these compartments, with mass exchange processes governing the transport and partitioning of chemical substances within and between these environmental compartments. This detailed compartmentalization reflects the diverse environmental media and land-use types typically found within regional and continental boundaries.[4,5]

At the global scale, the model structure adapts to accommodate climatic variability, consisting of the atmospheric compartment (air), the soil compartment, two oceanic compartments (surface ocean and deep ocean) and an ocean sediment compartment. The variation in the compartmental structure on the global scale is primarily due to differences in the dominant processes influencing chemical behavior. At the regional and continental scales, localized factors such as land use, soil composition, and the presence of inland water bodies significantly affect chemical fate, necessitating a more detailed compartmental approach. In contrast, on the global scale, the focus shifts to large-scale processes like atmospheric circulation and oceanic currents, which can be effectively represented with fewer, broader compartments (Fig. 4).[4,5]

The SimpleBox 4.04 model applies a mass balance approach to describe the fate and transport of chemicals in multiple environmental compartments at different spatial scales. It computes both the steady-state and quasi-dynamic chemical distributions, classifying it as a Mackay Level III/IV multimedia environmental fate model that operates under non-equilibrium conditions to simulate the distribution and transport of chemicals across multiple compartments. While most multimedia fate models adopt a fugacity-based approach that treats compartments as being in near-equilibrium and uses fugacity capacities (*Z*-values) to describe how readily chemicals partition between media, SimpleBox treats intermedia transport as a mass transfer process driven by bulk flow rather than by fugacity-driven diffusion.[12] This piston-like conceptualization

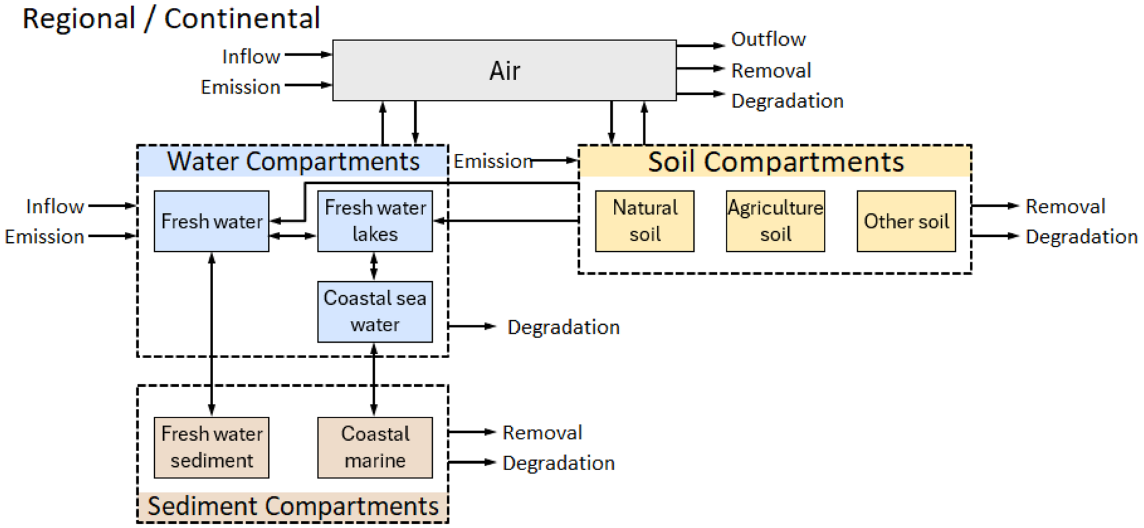


Fig. 3 Schematic representation of the SimpleBox 4.04 environmental compartments at the regional and continental scales. The model includes nine distinct compartments representing key environmental compartments: air, three soil compartments (natural soil, agricultural soil, and other soil), three water compartments (freshwater, freshwater lakes, and coastal seawater), and two sediment compartments (freshwater sediment and coastal marine sediment).

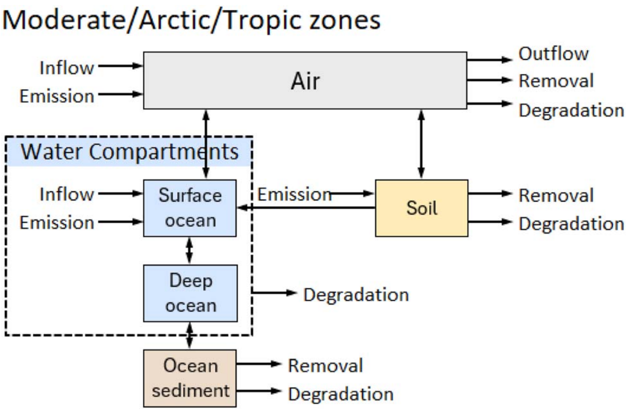


Fig. 4 Schematic representation of the SimpleBox 4.04 model compartments at the global scale. The model includes five key environmental compartments: air, soil, two oceanic compartments (surface ocean and deep ocean), and an ocean sediment compartment.

assumes that chemicals are physically transferred between compartments through advection, deposition, and sedimentation, with transfer rates determined by empirical environmental parameters (*e.g.*, wind-driven deposition, river flow, and soil runoff), rather than strict thermodynamic equilibrium.[1] This approach allows SimpleBox 4.04 to be more computationally efficient and applicable to complex regulatory scenarios, particularly when dealing with chemicals that do not rapidly equilibrate across compartments (*e.g.*, persistent pollutants, heavy metals, or ionizing compounds). The movement of chemicals within each compartment is dictated by various mass flow processes that regulate their entry, transfer, and removal. Chemicals can enter a compartment through intermedia transport from another box inside the spatial scale or *via* emissions and import flows of air or water from boxes outside the spatial scale to which the box belongs. On the other hand, chemicals can leave a compartment through intermedia transport to other boxes in the same spatial system, export to a different spatial scale and degradation due to chemical transformation.

To solve the system of mass balance equations in the SimpleBox model, matrix algebra is employed. For a system of n environmental compartments, the mass balance can be expressed in the matrix form as[6]

$$\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} = \mathbf{K} \times \mathbf{M} + \mathbf{E} \tag{1}$$

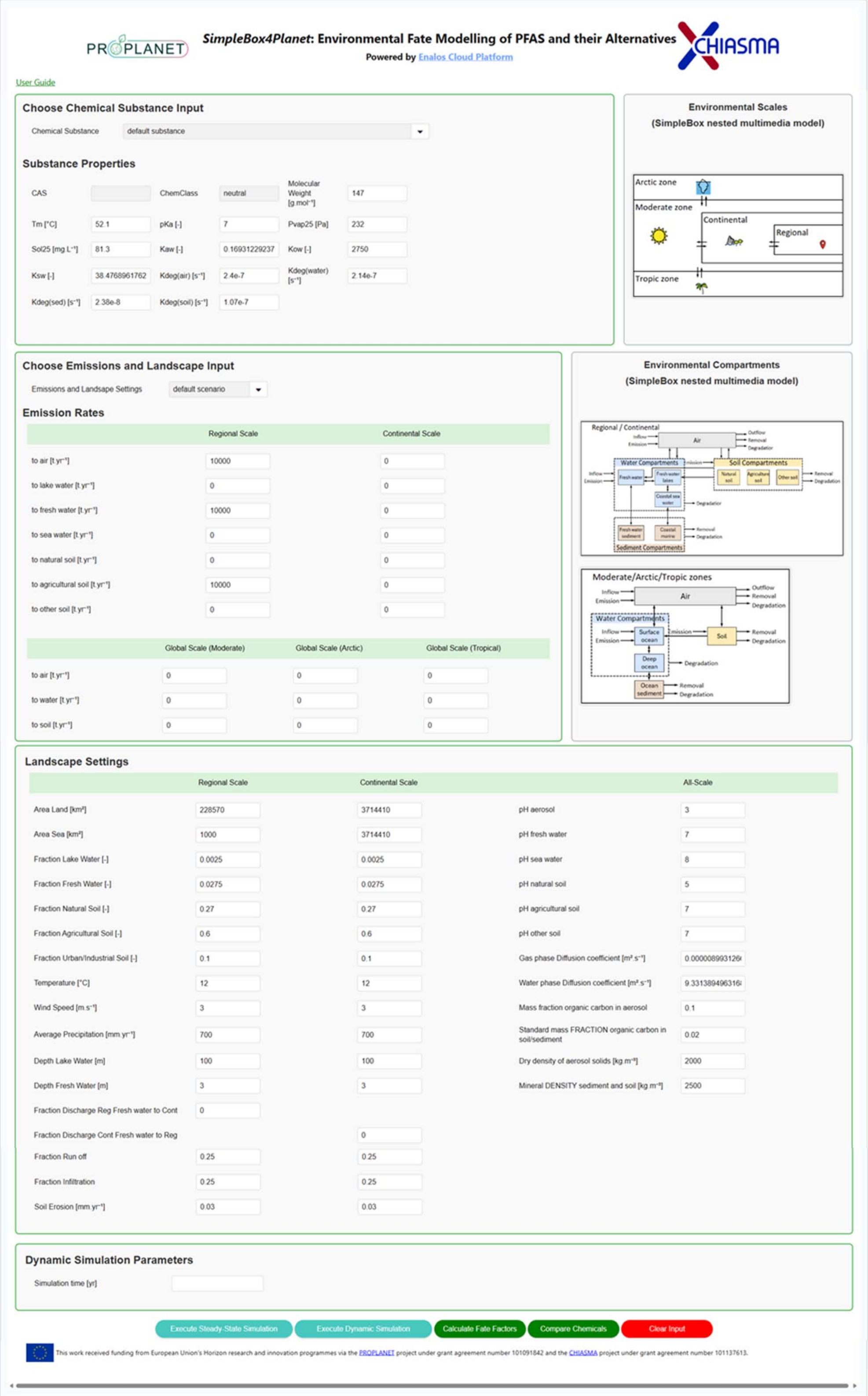
where **M** is the vector of chemical masses in each compartment, measured in kg per day ($\mathbf{M} \in \mathbb{R}^n$), **E** is the vector of emission rates into each compartment, measured in kg ($\mathbf{E} \in \mathbb{R}^n$), and **K** is the matrix of transfer rate coefficients between compartments, measured in per day ($\mathbf{K} \in \mathbb{R}^{n \times n}$). In the fully nested implementation (regional, continental and three global zones), **K** is a 33 × 33 model matrix that also includes the inter-scale exchange terms between regional, continental and global boxes. Assuming a steady-state condition (no accumulation $\mathrm{d}\mathbf{M}/\mathrm{d}t = 0$), the mass balance equation can be solved as

$$\mathbf{M} = -\mathbf{K}^{-1} \times \mathbf{E} \tag{2}$$

which gives the mass of the chemical in each compartment at the steady state. By definition, the fate matrix **FF** is defined as the negative inverse of the transfer rate matrix:[54]

$$\mathbf{FF} = -\mathbf{K}^{-1} \tag{3}$$

where the elements $\mathrm{FF}_{i,m}$ of the fate matrix (which have a unit of day) are called the fate factors, and they represent the increase in chemical mass in compartment i (kg) due to an emission into compartment m (kg per day).[54] The diagonal elements of the fate



SimpleBox4Planet: Environmental Fate Modelling of PFAS and their Alternatives

Powered by Enalos Cloud Platform

Choose Chemical Substance Input

Chemical Substance: default substance

Substance Properties

CAS		ChemClass	neutral	Molecular Weight [g mol^{-1}]	147
Tm [°C]	52.1	pKa [-]	7	Pvap25 [Pa]	232
Sol25 [mg L^{-1}]	81.3	Kaw [-]	0.16931229237	Kow [-]	2750
Ksw [-]	38.4768961762	Kdeg(air) [s^{-1}]	2.4e-7	Kdeg(water) [s^{-1}]	2.14e-7
Kdeg(sed) [s^{-1}]	2.38e-8	Kdeg(soil) [s^{-1}]	1.07e-7		

Choose Emissions and Landscape Input

Emissions and Landsape Settings: default scenario

Emission Rates

	Regional Scale	Continental Scale
to air [t yr^{-1}]	10000	0
to lake water [t yr^{-1}]	0	0
to fresh water [t yr^{-1}]	10000	0
to sea water [t yr^{-1}]	0	0
to natural soil [t yr^{-1}]	0	0
to agricultural soil [t yr^{-1}]	10000	0
to other soil [t yr^{-1}]	0	0

	Global Scale (Moderate)	Global Scale (Arctic)	Global Scale (Tropical)
to air [t yr^{-1}]	0	0	0
to water [t yr^{-1}]	0	0	0
to soil [t yr^{-1}]	0	0	0

Landscape Settings

	Regional Scale	Continental Scale		All-Scale
Area Land [km^2]	228570	3714410	pH aerosol	3
Area Sea [km^2]	1000	3714410	pH fresh water	7
Fraction Lake Water [-]	0.0025	0.0025	pH sea water	8
Fraction Fresh Water [-]	0.0275	0.0275	pH natural soil	5
Fraction Natural Soil [-]	0.27	0.27	pH agricultural soil	7
Fraction Agricultural Soil [-]	0.6	0.6	pH other soil	7
Fraction Urban/Industrial Soil [-]	0.1	0.1	Gas phase Diffusion coefficient [m^2 s^{-1}]	0.000008993126
Temperature [°C]	12	12	Water phase Diffusion coefficient [m^2 s^{-1}]	9.331389496316
Wind Speed [m s^{-1}]	3	3	Mass fraction organic carbon in aerosol	0.1
Average Precipitation [mm yr^{-1}]	700	700	Standard mass FRACTION organic carbon in soil/sediment	0.02
Depth Lake Water [m]	100	100	Dry density of aerosol solids [kg m^{-3}]	2000
Depth Fresh Water [m]	3	3	Mineral DENSITY sediment and soil [kg m^{-3}]	2500
Fraction Discharge Reg Fresh water to Cont	0			
Fraction Discharge Cont Fresh water to Reg		0		
Fraction Run off	0.25	0.25		
Fraction Infiltration	0.25	0.25		
Soil Erosion [mm yr^{-1}]	0.03	0.03		

Dynamic Simulation Parameters

Simulation time [yr]:

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Fig. 5 The landing page of the *SimpleBox4Planet* web application, which integrates the SimpleBox (version 4.04) model for assessing the fate and transport of chemicals in the environment. The GUI provides an intuitive platform for users to define the physicochemical properties of the chemical(s) of interest, emission settings and landscape parameters to be assessed.

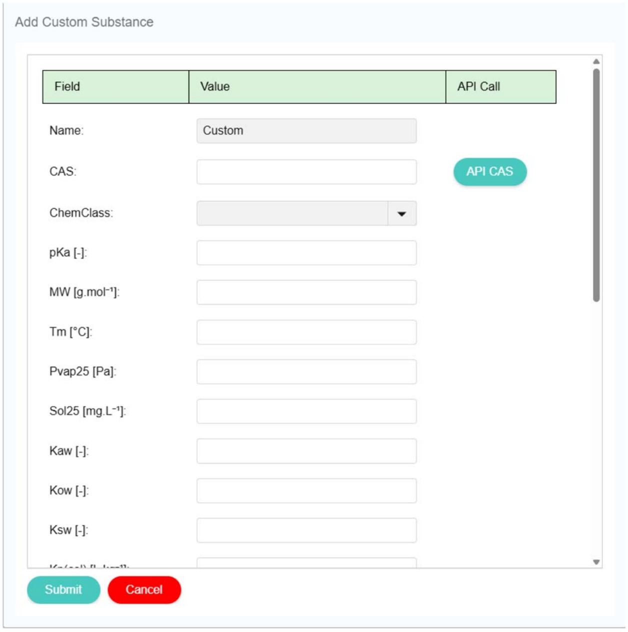
matrix, $FF_{m,m}$ represent the effective residence times in the respective compartments.[54] Within the *SimpleBox4Planet* web application, a built-in computational module is provided for calculating the fate matrix.

2.2 The *SimpleBox4Planet* web application

The *SimpleBox4Planet* web application, hosted on the Enalos Cloud Platform,[55] is accessible at https://www.enaloscloud.novamechanics.com/proplanet/simplebox4planet/ and https://www.enaloscloud.novamechanics.com/chiasma/simplebox4planet/. The backend of *SimpleBox4Planet* is implemented in the Java programming language and is designed to run the SimpleBox 4.04 Excel model, integrating user-defined input parameters from the web-based interface built with the ZK framework, an open-source Ajax web application framework implemented in Java.[56]

For quasi-dynamic simulations, a fourth-order Runge–Kutta numerical integration scheme is employed to solve the first-order differential mass balance equations governing the environmental fate of chemicals in *SimpleBox4Planet*. To solve this system dynamically, the Apache Commons Math library is employed, specifically utilizing the Classical Runge–Kutta Integrator to perform a fourth-order Runge–Kutta (RK4) integration. The simulation was executed in two distinct phases: an emission-driven buildup phase, followed by a decay phase, where emissions were set to zero, allowing natural dissipation. Thorough validation of the output generated between the SimpleBox 4.04 Excel and the *SimpleBox4Planet* web application is carried out to verify the output from the steady-state and dynamic calculations, as shown in Sections S1–S3 in the SI. An excellent agreement is found between the outputs generated by the SimpleBox 4.04 Excel file and the outputs generated by the *SimpleBox4Planet* web application, thus ensuring the robustness and accuracy of the web application implementation presented here.

As shown in Fig. 5, the Graphical User Interface (GUI) of *SimpleBox4Planet* is structured into four distinct sections to enhance clarity and facilitate user input. Specifically, the interface includes the Chemical Substance Input Section, the Emission Settings Input Section, the Landscape Parameters Input Section and the Dynamic Simulation Parameters Input Section. Within the Chemical Substance Input Section, users can select from a predefined list of PFASs and their alternatives. The various physicochemical properties of the predefined PFASs and their alternatives were retrieved from the CompTox Chemicals Dashboard (EPA).[14] Specifically, the full list of PFASs (~4000 substances) integrated within *SimpleBox4Planet* along with their CAS numbers is retrieved from the study of Mudlaff *et al.*[57] Physicochemical properties such as pK_a, M_w, T_m, P_{vap}, solubility and partition coefficients are retrieved in a consistent manner *via* an API from the EPA CompTox Chemicals Dashboard[14] to avoid cross-source discrepancies. For degradation rates and environmental half-lives, the default QSAR-based chemical-class parameters defined in the SimpleBox 4.04 model are used (neutral organics, acids, bases, hydrophobics, phenols, anilines, esters, triazines, *etc.*). Additionally, the interface offers a custom definition option, allowing users to manually input the physicochemical properties of a chemical of interest. When selecting the custom option, an interactive pop-up window (Fig. 6) is triggered, enabling users to enter detailed physicochemical parameters directly or indirectly *via* their CAS numbers. Within the interactive pop-up window for defining a custom chemical substance (Fig. 6), users have the option to define a chemical by its Chemical Abstracts Service (CAS) registry number and retrieve its physicochemical properties automatically. By clicking the 'API CAS' button, the system queries the CompTox Chemicals Dashboard (EPA)[14] to extract key properties, including molecular weight, acid dissociation constant (pK_a), melting temperature, vapor pressure, solubility, and octanol–water partitioning coefficient (K_{ow}). This feature enhances the usability of *SimpleBox4Planet*, allowing users to efficiently incorporate accurate physicochemical data into their environmental fate modelling simulations. Each selected chemical can be classified into predefined chemical classes based on the original SimpleBox 4.04 model, which integrates Quantitative Structure–Activity Relationships (QSARs) to estimate the solid–water partitioning coefficient.[5] The available chemical classes include neutral compounds, acids, bases, metals, hydrophobics, non-hydrophobics, phenols, anilines, benzonitriles, nitrobenzenes, acetanilides, carbamates, esters, phenylureas, phosphates, triazines, triazoles, uracils, alcohols, organic acids, amides, and dinitroanilines.

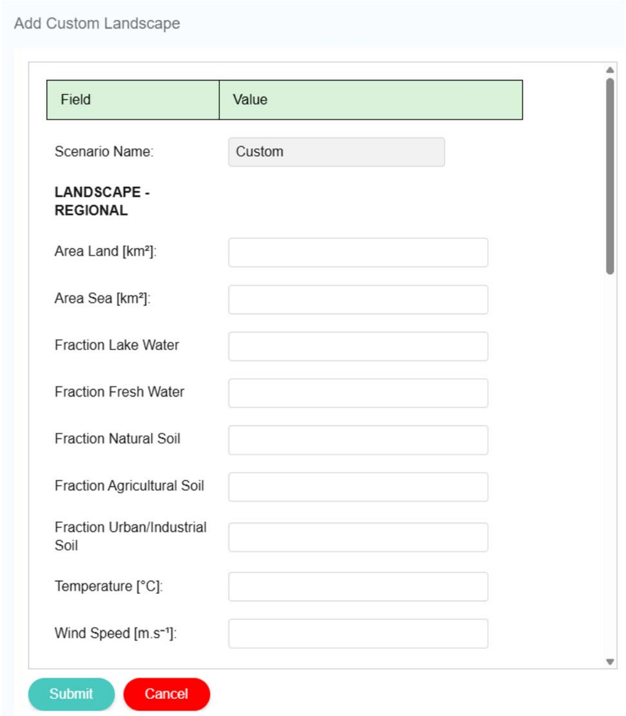


Add Custom Substance

Field	Value	API Call
Name:	Custom	
CAS:		API CAS
ChemClass:		
pKa [-]:		
MW [g.mol⁻¹]:		
Tm [°C]:		
Pvap25 [Pa]:		
Sol25 [mg.L⁻¹]:		
Kaw [-]:		
Kow [-]:		
Ksw [-]:		

Fig. 6 An interactive pop-up window for defining a custom chemical substance in *SimpleBox4Planet* to manually input physicochemical properties. Additionally, users can enter a CAS number and utilize the 'API CAS' button to automatically retrieve physicochemical data from the CompTox Chemicals Dashboard (EPA) if such data are available.[14]

Within the Emission Settings Input Section, users can specify emission values for different environmental compartments directly through the GUI, enabling users to define emissions at the desired scale for the corresponding


Add Custom Landscape

Field	Value
Scenario Name:	Custom
LANDSCAPE - REGIONAL	
Area Land [km^2]:	
Area Sea [km^2]:	
Fraction Lake Water	
Fraction Fresh Water	
Fraction Natural Soil	
Fraction Agricultural Soil	
Fraction Urban/Industrial Soil	
Temperature [°C]:	
Wind Speed [$m.s^{-1}$]:	

Fig. 7 An interactive pop-up window for manually defining landscape settings in *SimpleBox4Planet*.

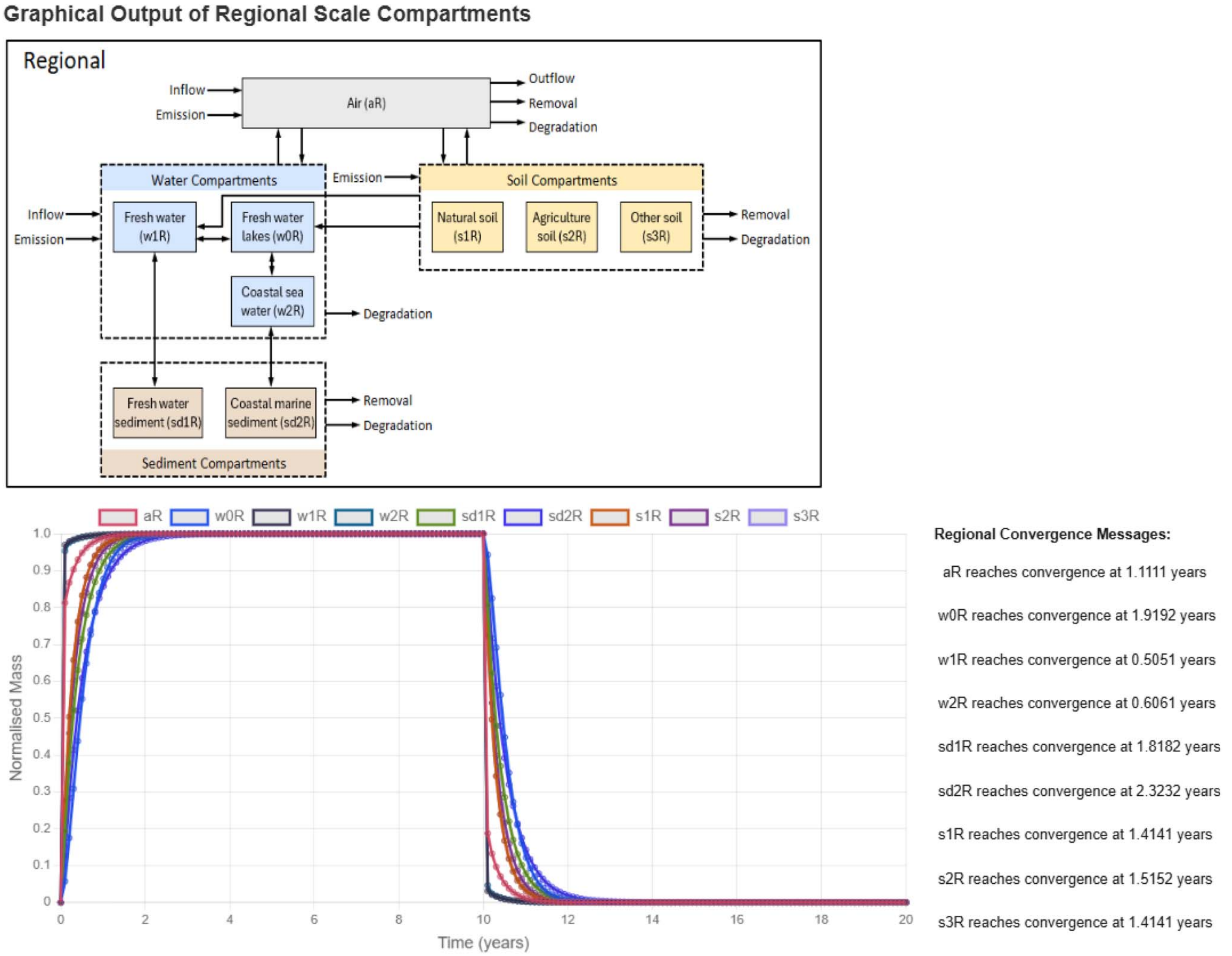
compartment. The SimpleBox 4.04 model does not permit direct emissions to sediment compartments, and therefore, the GUI does not provide an emission input option for sediments in *SimpleBox4Planet*. In the Landscape Settings Input Section, users can configure landscape parameters by either selecting from default settings or choosing from a set of predefined landscapes available in the SimpleBox 4.04 database. These include the standard EUSES landscape,[58,59] 17 sub-continental landscapes,[5] and a default landscape that resembles the environmental characteristics of the Northern Hemisphere. Additionally, users have the option to manually define landscape parameters by selecting the custom option, which opens an interactive pop-up window (Fig. 7), allowing for precise user-defined landscape configurations. Within the Dynamic Simulation Parameters Input Section, users can manually specify the desired simulation duration in years for executing the dynamic simulation.

When users select the 'Execute Steady-State Simulation' button, a new window opens displaying the simulation outputs. This window provides a brief description of the steady-state simulation, followed by a comprehensive table presenting the steady-state masses and concentrations for each scale and compartment. The output generated in this window is shown in Section S4 of the SI. Users also have the option to export the results in Excel format by clicking the 'Export Results' button. Below the table, a graphical representation of the mass distribution across different scales is displayed, illustrating both the mass within each scale and the total mass calculated across all scales. For further analysis, next to each mass calculation, a 'Show' button is available, allowing users to visualize the mass distribution within each scale across individual compartments through interactive graphical outputs. Additionally, a second table provides detailed information on steady-state mass flows at each scale and for each compartment. This includes mass transfer processes such as emission, inflow, outflow, removal, degradation, air–water exchange, water–air exchange, air–soil exchange, soil–air exchange, soil–water exchange, water–sediment exchange, and sediment–water exchange. The table also includes a mass balance verification column, ensuring that input flows equal output flows, thereby confirming the accuracy of the steady-state calculations. Users can export these results using the 'Export Mass Flows' button, allowing for in-depth data analysis and reporting in Excel format.

The 'Execute Dynamic Simulation' option can be selected only if the user has predefined the simulation duration (in years) within the GUI. Once this button is activated, a new window opens, initially providing a brief description of the quasi-dynamic simulation process. The interface then presents a graphical representation of mass distribution across different scales, allowing users to explore the dynamic evolution of mass over time. By selecting the 'Show' button for a specific scale, users can visualize the time-dependent changes in mass, normalized by the steady-state mass (normalized mass), as a function of the user-defined simulation duration, as shown in Fig. 8. The graphical output depicts the mass evolution within each compartment for the selected scale, offering insights into the temporal behavior of chemical fate and transport. A comprehensive representation of this output window is provided in Section S5 of the SI.

The 'Calculate Fate Factors' button initiates the computation of fate factors based on the user-defined environmental scenario. This computation is only enabled when the user specifies an emission into a single compartment at the continental scale. If the user selects more than one compartment for emission or defines the scenario at the regional or global scale, the application will disable the fate factor computation, as the calculation is only valid and meaningful for single-compartment emissions at the continental level. This constraint ensures consistency with the theoretical assumptions underlying the fate matrix derivation in the model.[54] The output of the fate factor computation is shown in Section S6 of the SI, where users can also define the time (in years) over which they wish to evaluate the fate behavior of the chemical.

SimpleBox4Planet also features a comparative analysis tool that allows users to evaluate multiple chemicals under identical emission and landscape settings. This tool facilitates the assessment of total mass distribution across environmental scales and compartments, enabling the identification of chemicals that exhibit the lowest overall environmental burden. By comparing mass distributions, users can systematically assess potential alternatives to PFASs, aiding in the selection of more environmentally sustainable chemical substitutes. When users opt to compare chemicals, a new window opens, where they can select the specific chemicals for analysis. Upon clicking 'Execute', the system generates a bar chart (Fig. 9), visually comparing the total mass distributed across environmental compartments for each selected chemical. Users also have the



Graphical Output of Regional Scale Compartments

Regional Convergence Messages:

aR reaches convergence at 1.1111 years

w0R reaches convergence at 1.9192 years

w1R reaches convergence at 0.5051 years

w2R reaches convergence at 0.6061 years

sd1R reaches convergence at 1.8182 years

sd2R reaches convergence at 2.3232 years

s1R reaches convergence at 1.4141 years

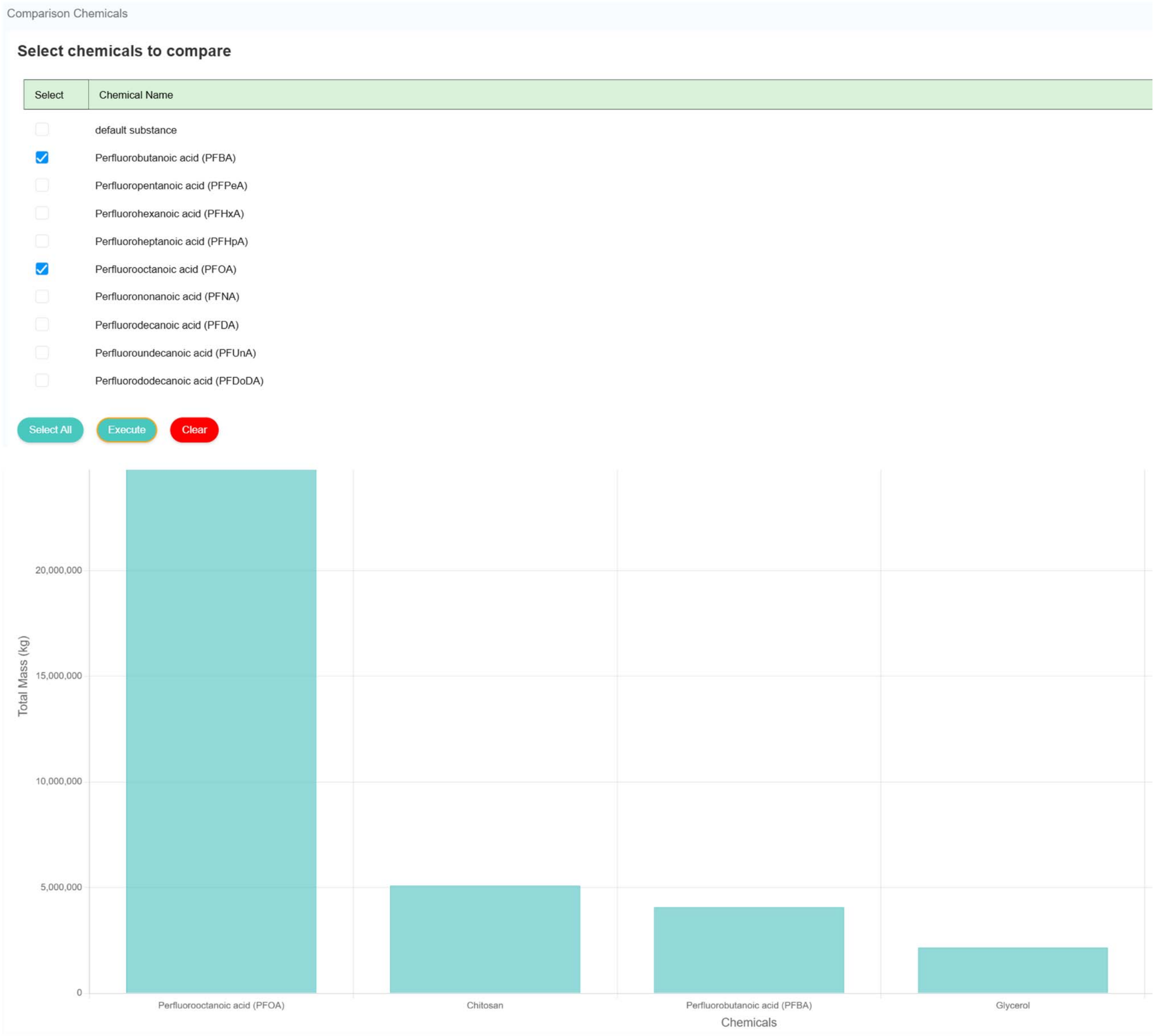
s2R reaches convergence at 1.5152 years

s3R reaches convergence at 1.4141 years

Fig. 8 A graphical output of the dynamic evolution of mass, normalized by the steady-state mass, as a function of time illustrating the temporal changes in mass within each compartment for the selected scale based on the user-defined simulation duration, as generated within the *SimpleBox4Planet* web application. Compartment labels at the regional scale are denoted by aR: air, w0R: fresh water lakes, w1R: fresh water, w2R: coastal sea water, s1R: natural soil, s2R: agricultural soil, s3R: other soil, sd1R: fresh water sediment and sd2R: coastal marine sediment.

flexibility to select all available chemicals for a comprehensive comparative analysis. This feature provides a data-driven approach to chemical substitution, supporting informed decision-making in regulatory assessments and sustainable materials design.

The *SimpleBox4Planet* web application features a Representational State Transfer (REST) application programming interface (API) designed to facilitate integration with external systems, thereby enhancing interoperability and extending its utility in various environmental modelling and regulatory contexts. These APIs include two GET endpoints (https://enaloscloud.novamechanics.com/proplanet/apis/sb4p/scenarios or https://enaloscloud.novamechanics.com/chiasma/apis/sb4p/scenarios and https://enaloscloud.novamechanics.com/proplanet/apis/sb4p/substances or https://enaloscloud.novamechanics.com/chiasma/apis/sb4p/substances) that retrieve the chemical substance and landscape and emission settings defined in the *SimpleBox4Planet* and one POST endpoint (https://enaloscloud.novamechanics.com/proplanet/apis/sb4p/results/ or https://enaloscloud.novamechanics.com/chiasma/apis/sb4p/results/) that enables users to submit simulation parameters and receive output results of the steady-state calculations. To demonstrate the functionality and accessibility of these APIs, the SI includes detailed documentation of the API interactions using Postman in Section S7 of the SI. Incorporating RESTful APIs not only enhances the flexibility, scalability and interoperability of environmental modelling applications but also aligns with the FAIR (Findable, Accessible, Interoperable and Reusable) and FAIR4ResearchSoftware (FAIR4RS) principles,[60,61] ensuring that data and computational models can be shared, reused and integrated across platforms. By enabling standardized data exchange, these APIs facilitate the integration of environmental models into broader decision-support frameworks, thereby strengthening evidence-based policy-making and advancing sustainable-by-design (SSbD) materials development. Furthermore, the integration of the *SimpleBox4Planet* web application within the Enalos Cloud



Comparison Chemicals

Select chemicals to compare

Select	Chemical Name
☐	default substance
☑	Perfluorobutanoic acid (PFBA)
☐	Perfluoropentanoic acid (PFPeA)
☐	Perfluorohexanoic acid (PFHxA)
☐	Perfluoroheptanoic acid (PFHpA)
☑	Perfluorooctanoic acid (PFOA)
☐	Perfluorononanoic acid (PFNA)
☐	Perfluorodecanoic acid (PFDA)
☐	Perfluoroundecanoic acid (PFUnA)
☐	Perfluorododecanoic acid (PFDoDA)

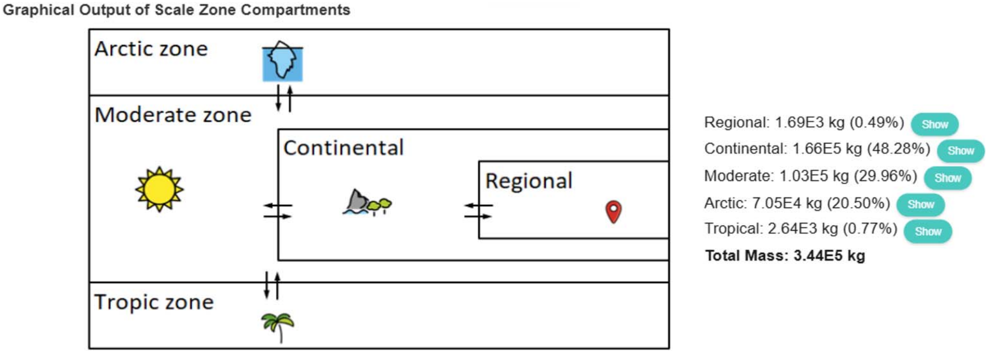
Fig. 9 The interactive comparison window in *SimpleBox4Planet* for evaluating multiple chemicals under identical emission and landscape conditions. Users can select specific chemicals or opt to compare all available substances to assess their total mass distribution across environmental scales and compartments. Upon execution, a bar chart is generated to visualize the comparative environmental impact of each chemical, aiding in the identification of less persistent alternatives.

Platform enhances its FAIR compliance by allowing users to find, access, and interact with other hosted free-to-use web applications within the nano-informatics framework (*e.g.*, LungDepo,[62] MicroPlasticFate,[63] NanoBioAccumulate,[64] NanoTube Construct,[65] NanoXtract,[66] NInChI,[67] NanoConstruct,[68] EcoTox,[69] and SafeNanoScope[70]) and beyond.[63–73]

Although *SimpleBox4Planet* can, in principle, be parameterised for any substance for which the required input data are available, its current implementation follows the generic SimpleBox model (version 4.04) and is therefore most appropriate for neutral and ionizable organic chemicals.[4,5,12] For chemical classes, such as metals, whose environmental fate is dominated by complex speciation and redox-dependent processes, the use of bulk partition coefficients and first-order degradation rates may not fully capture mechanistic behaviour, and results should be interpreted as screening-level indicators unless supported by additional metal-specific speciation modelling.[74]

3 Case study using *SimpleBox4Planet*

In this section, the practical application of the *SimpleBox4Planet* web application is demonstrated through a case study focusing on the environmental fate and transport of perfluorooctanoic acid (PFOA), a well-characterized and extensively studied PFAS that belongs to the class of perfluoroalkyl carboxylic acids



Regional: 1.69E3 kg (0.49%)
Continental: 1.66E5 kg (48.28%)
Moderate: 1.03E5 kg (29.96%)
Arctic: 7.05E4 kg (20.50%)
Tropical: 2.64E3 kg (0.77%)
Total Mass: 3.44E5 kg

Fig. 10 Mass distribution of perfluorooctanoic acid (PFOA) across spatial environmental scales following direct emissions of 1000 tonnes per year to air at the continental scale, as simulated by the *SimpleBox4Planet* web application.

(PFCAs),[75] known for their environmental persistence and mobility.[17,40,44,52,53] This case study shows how *SimpleBox4Planet* can be used to analyze and compare the distribution of PFOA across different environmental compartments (air, water, soil, sediment, *etc.*) and across multiple spatial scales (continental, regional, and global). The objective is to support science-based decision-making regarding the environmental behavior and potential harm of PFOA, as well as its alternatives, by evaluating the total mass distribution and their potential impact across environmental media. A statistical analysis is also conducted to highlight the effect of physicochemical properties on the transport and fate (behavior) of PFOA. Notably, the *SimpleBox4Planet* platform supports a wide range of predefined PFAS compounds, offering users the flexibility to explore the fate and transport of numerous emerging PFASs beyond the one covered in this section.

3.1 Environmental transport of PFOA

The physicochemical properties used in the *SimpleBox4Planet* web application to model the steady-state environmental transport of perfluorooctanoic acid (PFOA) are presented in Fig. S12 in the SI. These properties have been obtained from previous studies.[75–78] According to numerous studies,[40,79–81] long-range environmental transport of PFOA occurs primarily *via* atmospheric and oceanic pathways, while soil-mediated transport is negligible. To investigate this transport behaviour, model simulations were conducted using the *SimpleBox4Planet* platform under three distinct emission scenarios, each assuming a direct source of 1000 tonnes per year on a continental scale: (i) emissions to air only, (ii) emissions to seawater only, and (iii) emissions to natural soil environments (*e.g.*, forested landscapes). These emission values were selected for comparative purposes and are intended to qualitatively explore the relative importance of different environmental pathways. The simulations were executed using the default continental-scale environmental settings of the original SimpleBox model, which are designed to reflect environmental conditions in the Northern Hemisphere.[5] For users seeking to perform more quantitatively robust assessments, the platform allows the incorporation of real-world emission estimates, such as those reported by Armitage *et al.*[79,82] who used the BETR Global and GloboPOP fate models to model the global transport and fate of PFOA and PFO in which they have considered direct emissions to range from 2700 to 5140 tonnes between 1950 and 2004, and from 475 to 932 tonnes between 2005 and 2050 (the lower values here being consistent with PFOA production being phased out in the US since 2015 and banned in the EU from 2020) under the POPs Regulation.[83]

Model simulations performed using the *SimpleBox4Planet* web application under the scenario of direct emissions of PFOA to air (1000 tonnes per year) reveal distinct patterns of spatial (and compartmental) distribution across environmental scales. As shown in Fig. 10, approximately 48% of the total mass remains within the continental scale, while only a minor fraction (∼0.5%) is transported to the regional scale. A substantial portion, nearly 50%, is subject to long-range environmental transport to the global scale, with approximately 30% distributed to the moderate zone, 20% to the arctic, and ∼1% to the tropical zone. It is interesting to note that if emissions were considered on the regional scale, a similar behavior is observed, as shown in Fig. S13 in the SI, where around 15% of total mass remains on the regional scale, 42% is on the continental scale and around 44% on the global scale with more in the moderate and arctic zones and almost negligible in the tropical zone. Comparable behavior is also evident in the scenario where emissions are released directly to seawater (Fig. S14). Here, approximately 56% of the distributed mass remains within the continental scale, with minimal transfer to the regional scale. The remainder is distributed globally, primarily in the moderate and arctic zones, with only a negligible fraction reaching the tropical zone. In contrast, when emissions occur directly to natural soils (*e.g.*, forested areas), as seen in Fig. S15, the model predicts a higher degree of mass retention at the continental scale, approximately 76%, with the remaining mass again following the established trend: highest transfer to the moderate zone, followed by the arctic, and minimal transport to the tropics. These findings collectively emphasize the consistency of PFOA's long-range transport behavior across different emission scenarios, with enhanced transport toward cooler climatic zones (moderate and arctic), consistent with previous studies.[40,79,82]

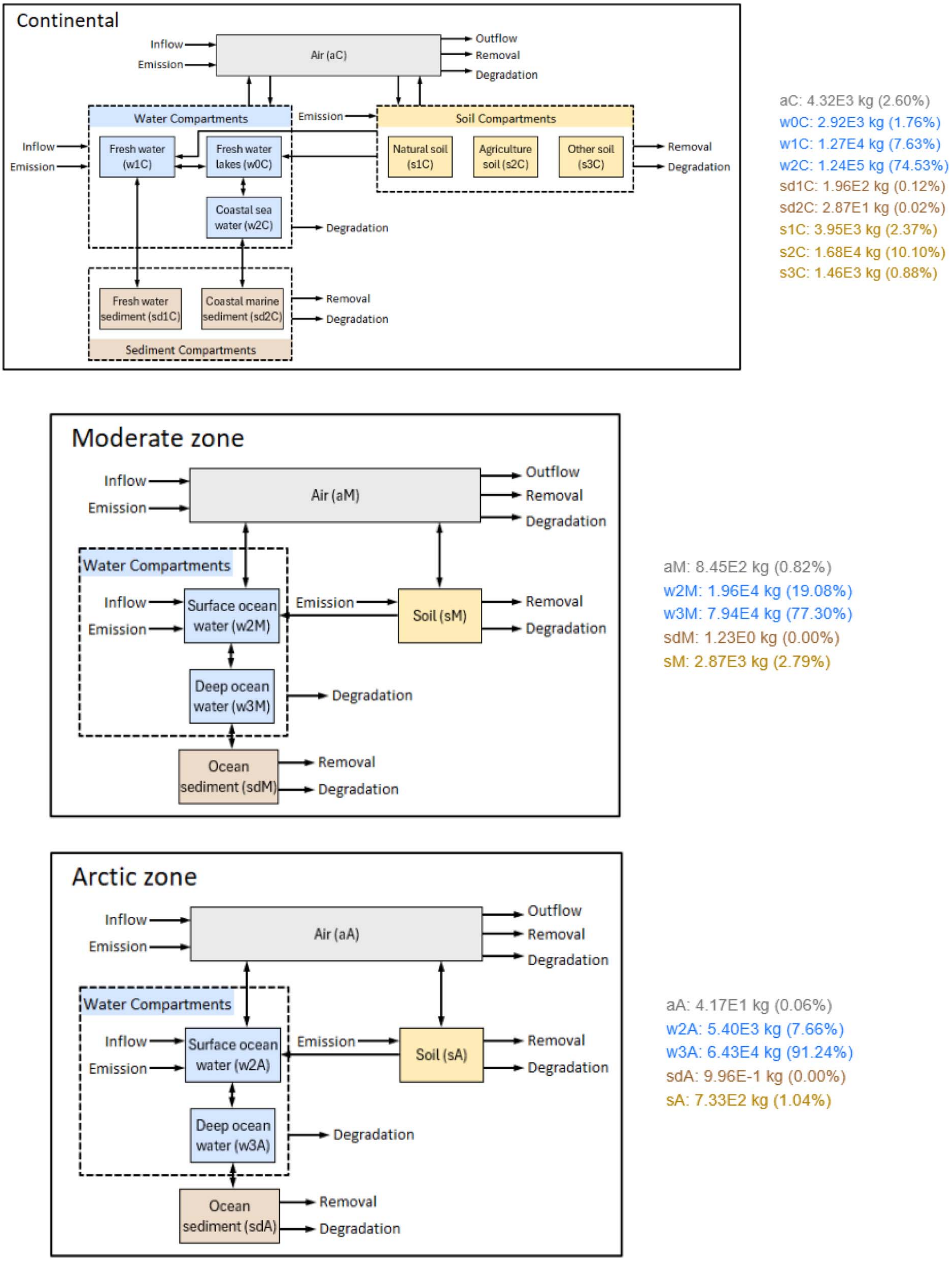
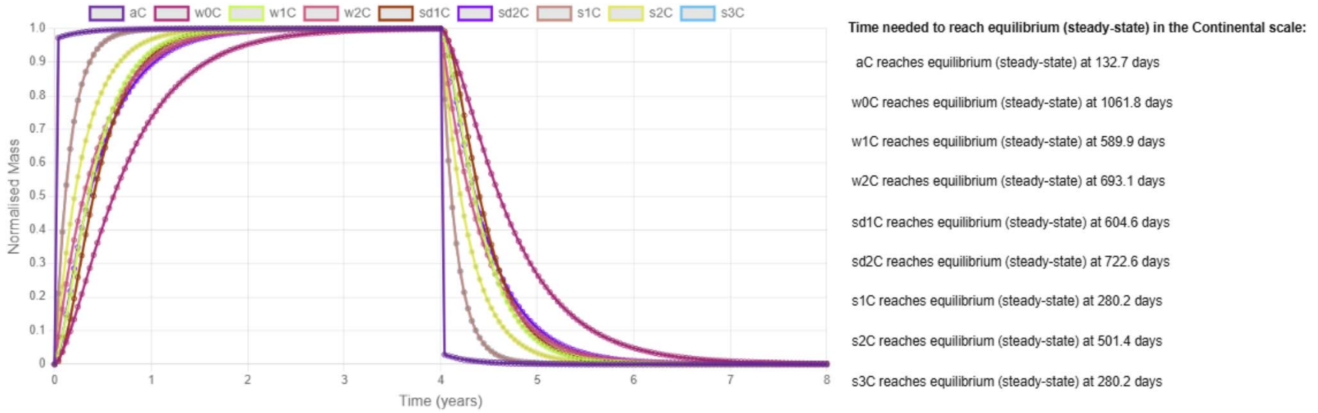


Fig. 11 Compartmental-level mass distribution of perfluorooctanoic acid (PFOA) simulated using the *SimpleBox4Planet* web application under a direct emission scenario of 1000 tonnes per year released to air at the continental scale. The figure illustrates the percentage of PFOA mass distributed across four environmental compartments, air, water, soil, and sediment, within the continental scale and the moderate and arctic zones of the global scale.

Additionally, results regarding the total mass of PFOA distributed across the environment vary significantly depending on the initial emission compartment, despite using an equivalent emission load of 1000 tonnes per year in each scenario. Specifically, direct emissions to seawater result in the highest environmental burden, with approximately 672 tonnes of PFOA (Fig. S14) remaining distributed across environmental compartments. In comparison, direct emissions to natural soil result in a slightly lower but still substantial distribution of around 606 tonnes (Fig. S15), while emissions to air yield the lowest total distributed mass, at approximately 344 tonnes (Fig. 10). These findings suggest that direct discharges to aquatic systems, particularly seawater, may pose the greatest risk of widespread environmental contamination, primarily due to PFOA's high water solubility, low degradability, and strong persistence in marine environments. Emissions to soil also result in considerable long-term distribution, highlighting the potential for leaching and subsequent transport to groundwater or surface waters. In contrast, emissions to air, while still significant, are comparatively less persistent due to atmospheric dispersion and eventual deposition, leading to lower cumulative environmental mass. Overall, these results underscore the importance of controlling point-source discharges, especially to aquatic and terrestrial compartments, to mitigate the long-range transport and accumulation of persistent pollutants such as PFOA.

The compartmental mass distribution patterns of PFOA are visually summarized in Fig. 11, which illustrates the environmental partitioning of PFOA across air, water, soil, and sediment compartments within the continental scale and the moderate and arctic zones of the global scale. It is revealed that under a direct emission scenario of 1000 tonnes per year of PFOA released to air at the continental scale, the majority of the retained mass (~84%) partitions into aquatic compartments. Within this domain, coastal seawater emerges as the dominant sink, accounting for approximately 74.5% of the total mass. A relatively small fraction (~2.6%) remains in the atmospheric compartment, while around 13% distributes into soil compartments. Sediment compartments accumulate only negligible amounts, consistent with the physicochemical behavior of PFOA, including its high water solubility, low vapor pressure, limited sorption to organic matter, and low partitioning tendency to particulates, all of which contribute to its preferential distribution in the aqueous phase. In contrast, on the global scale, particularly within the moderate and arctic zones, the distribution is even more strongly toward the aquatic environment. Between 96% and 99% of the transported PFOA mass is found in water compartments, with over 77% specifically residing in deep ocean waters. The contributions of air and sediment compartments are minimal, and only 1–3% of the mass is retained in soil. These findings underscore PFOA's high mobility and persistence in the hydrosphere, as well as its propensity for long-term accumulation in marine environments, particularly coastal seawater at the continental level and deep ocean waters in the global zones. A similar compartmental distribution pattern is observed when direct emissions at the continental scale are released into seawater (see Fig. S16). In this scenario, nearly 100% of the emitted PFOA mass remains within aquatic compartments across all spatial scales. At the continental scale, the entirety of the retained mass is found in coastal seawater. At the global scale, both the moderate and arctic zones exhibit strong partitioning into deep ocean waters, with approximately 80% and 92%, respectively, of the transported mass residing in these compartments. The remaining fractions are distributed in surface ocean waters, with negligible amounts present in atmospheric, soil, or sediment compartments. In the case of direct emissions to natural soil at the continental scale (see Fig. S17), the distribution pattern differs slightly. Here, approximately 34% of the total mass is retained in soil compartments, while the remaining 66% partitions into aquatic media. Despite the differences in initial compartmental allocation, long-range transport dynamics to the global scale remain consistent across emission scenarios. For both the moderate and arctic zones, regardless of whether the initial



Time needed to reach equilibrium (steady-state) in the Continental scale:

aC reaches equilibrium (steady-state) at 132.7 days

w0C reaches equilibrium (steady-state) at 1061.8 days

w1C reaches equilibrium (steady-state) at 589.9 days

w2C reaches equilibrium (steady-state) at 693.1 days

sd1C reaches equilibrium (steady-state) at 604.6 days

sd2C reaches equilibrium (steady-state) at 722.6 days

s1C reaches equilibrium (steady-state) at 280.2 days

s2C reaches equilibrium (steady-state) at 501.4 days

s3C reaches equilibrium (steady-state) at 280.2 days

Fig. 12 Time-resolved simulation of the normalized mass of PFOA in each environmental compartment at the continental scale, conducted using the *SimpleBox4Planet* web application under a direct air emission scenario of 1000 tonnes per year. The y-axis represents the normalized mass (*i.e.*, the ratio of dynamic mass to steady-state mass), where a value of 1 indicates that the steady state has been reached. The figure also shows the time to equilibrium for each compartment, annotated in days, and demonstrates that the time required to reach the steady state during the emission phase equals the time required for mass decay following emission cessation, consistent with first-order kinetic behavior.

emission occurs to air, water, or soil at the continental scale, the transported PFOA mass is found exclusively in aquatic compartments. In these zones, more than 78% of the mass accumulates in deep ocean waters, with the remainder residing in surface ocean layers. These results further highlight the dominant role of aquatic pathways in the global-scale transport and environmental persistence of PFOA, reinforcing its classification as a highly mobile and persistent organic pollutant with a strong tendency for long-term marine accumulation. It is important to note, however, that the results presented here should be interpreted as screening-level conceptual outputs, as parameter uncertainties (*e.g.*, degradation rates and partition coefficients) limit accurate and reliable quantitative prediction of environmental concentrations at the global scale.

3.2 Environmental dynamics and fate of PFOA

Following the analysis of the steady-state transport of PFOA across environmental scales and compartments, this section extends the investigation to assess the dynamic behavior and environmental fate of PFOA at the compartmental level within the continental scale using the *SimpleBox4Planet* web application. The objective is to quantify the persistence of PFOA in individual environmental media by calculating the fate factor (see eqn (3)), a critical metric for evaluating a chemical substance's potential to persist and be transported across environmental compartments. Similar to the previous section, three discrete emission scenarios were modeled, each assuming a direct emission of 1000 tonnes per year into a specific environmental compartment at the continental scale: (i) air, (ii) seawater, and (iii) natural soil to evaluate the fate of PFOA.

Fig. 12 presents the results of the dynamic simulation conducted over an 8-year period, using the *SimpleBox4Planet* web application to assess the time-dependent behavior of PFOA at the continental scale. The simulation assumes constant direct emissions to air at a rate of 1000 tonnes per year for the first 4 years, followed by zero emissions for the subsequent 4 years, to analyze both the buildup and decay phases of PFOA mass in each environmental compartment. The *y*-axis displays the normalized mass (*i.e.*, the ratio of dynamic mass to steady-state mass), allowing for the clear identification of the time to steady-state, as a normalized value of 1 indicates that equilibrium has been reached. The corresponding time to reach the steady state, expressed in days, is also shown within the figure. As described by the first-order differential equation governing mass transport and degradation (see eqn (1)), the time required for a compartment to reach the steady state under constant emissions is equivalent to the time required for the mass to decay to negligible levels following cessation of emissions. The results for emissions directed to seawater and natural soil are shown in Fig. S18 and S19 in the SI, respectively. In all three scenarios, PFOA concentrations across compartments reach steady-state in less than 4 years.

The fate factor is next calculated using the year 4 time point, at which the steady state was confirmed, and by determining the residence time of PFOA in each compartment under the different emission scenarios. The results are summarized in Table 1. Under the air emission scenario, coastal seawater exhibited the highest persistence, with an estimated fate factor of approximately 45 days, followed by agricultural soil (~6 days) and freshwater (~5 days). Lower persistence was observed in air (~1.6 days), lakes and natural soil (~1 day each), while other compartments exhibited negligible retention. In the scenario of direct emissions to seawater, coastal seawater again demonstrated dominant retention, with an exceptionally high persistence of approximately 136 days, while no meaningful persistence was observed in any other compartment. This finding reinforces the strong affinity of PFOA for the aqueous phase. In the natural soil emission scenario, the highest fate factors were observed in both natural soil and coastal seawater, with residence times of approximately 54 days. Notably, freshwater also showed high persistence (~47 days) with freshwater lakes showing moderate persistence (~11 days), while agricultural soil retained PFOA for a shorter duration (~2 days), and air again contributed negligibly. These patterns agree with the steady-state simulations, where transport to aquatic systems remained dominant, even when emissions originated from terrestrial compartments. Overall, these dynamic simulations further highlight that PFOA, regardless of the emission scenario, rapidly partitions into aquatic compartments where it exhibits high environmental persistence, especially in coastal ocean waters. The integration of time-dependent modelling provides a more comprehensive perspective on compartment-specific residence times, offering valuable insights for regulatory risk assessments and the development of mitigation strategies for persistent organic pollutants like PFOA.

Table 1 Fate factor values (in days) for PFOA in each environmental compartment at the continental scale, calculated using the *SimpleBox4Planet* web application under three distinct direct emission scenarios: (i) 1000 tonnes per year to air, (ii) 1000 tonnes per year to seawater, and (iii) 1000 tonnes per year to natural soil

	Air	Seawater	Natural soil
Air	1.6	0.0	0.5
Fresh water lake	1.1	0.0	10.6
Fresh water	4.6	0.0	46.5
Coastal seawater	45.3	136.4	53.6
Natural soil	1.4	0.0	54.3
Agricultural soil	6.1	0.0	2.1
Other soil	0.5	0.0	0.2

While multimedia fate modelling provides essential information on persistence, long-range transport and environmental distribution, Safe-and-Sustainable-by-Design (SSbD) assessments, such as those outlined in the European Commission's SSbD framework and the OECD guidance on safer chemical alternatives, also require integration with toxicological and ecotoxicological evidence, including hazard characterisation, bioaccumulation potential and mechanistic toxicity endpoints.[84] *SimpleBox4Planet* therefore serves as the environmental exposure component of SSbD evaluation and should be complemented with substance-specific hazard data and life-cycle considerations to support comprehensive, safe-and-sustainable chemical substitution.[84] A key advantage of

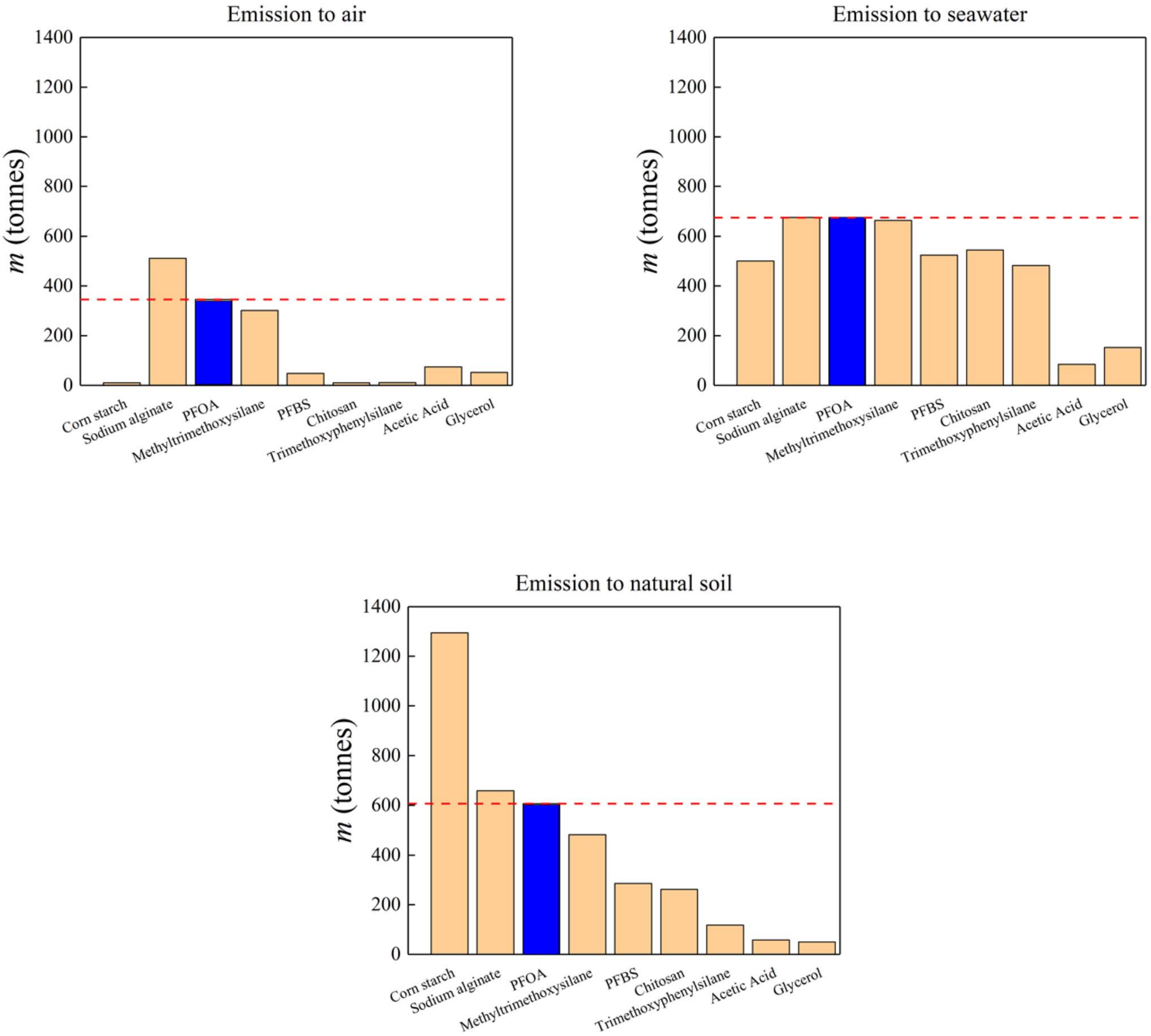


Fig. 13 Total environmental mass distribution of PFOA (highlighted with the blue bar) and selected alternative substances under three distinct continental-scale emission (1000 tonnes per year) scenarios: (i) direct emission to air, (ii) direct emission to seawater, and (iii) direct emission to natural soil. A dashed red horizontal line is included in each plot to indicate the total predicted environmental mass of PFOA, providing a visual benchmark for evaluating the relative environmental persistence of each alternative substance.

SimpleBox4Planet is that its output format is suited for direct upload into other tools in the Enalos Cloud Platform such as LungDepo[62] and NanoBioAccumulate.[64]

3.3 Alternatives to PFOA

The *SimpleBox4Planet* web application offers comparative environmental assessments by allowing users to input and simulate the environmental behavior of a wide range of chemicals, including PFAS substitutes, under identical emission scenarios. Specifically, users can compare the total mass distributed, which is particularly valuable in the context of assessing replacements such as short-chain PFASs (*e.g.*, perfluorobutanesulfonic acid, PFBS), fluorine-free or bio-based alternatives such as starch (corn starch), sodium alginate, chitosan, glycerol and acetic acid, or other synthetic hydrophobic agents such as methyltrimethoxysilane and trimethoxyphenylsilane, which are currently being explored in the literature as potential alternatives to legacy compounds like PFOA.[85,86] Although 530 PFAS-free alternatives were already identified in the literature,[50] the objective here was not to screen all possible alternatives, but rather to demonstrate the comparative capability of the *SimpleBox4Planet* web application using a representative subset of alternatives. The selected alternatives were chosen based on their chemical diversity, enabling illustration of the model's behaviour across bio-based materials, short-chain PFASs, and synthetic hydrophobic agents, the availability of complete physicochemical property data and their industrial and environmental relevance.

Fig. 13 presents the total environmental mass distribution for PFOA and its proposed alternatives across all environmental scales under three distinct continental-scale emission scenarios: (i) direct emission to air (1000 tonnes per year), (ii) direct emission to seawater (1000 tonnes per year), and (iii) direct emission to natural soil (1000 tonnes per year). The results reveal clear distinctions in environmental mass distribution depending on both the chemical identity and the emission pathway. Under the air emission scenario, sodium alginate shows a higher total environmental mass than PFOA, with methyltrimethoxysilane closely matching PFOA in magnitude. All other alternatives, including corn starch, PFBS, chitosan, glycerol, and acetic acid, exhibit significantly lower environmental retention, suggesting reduced persistence and transport. For emissions to seawater, PFOA, sodium alginate, and methyltrimethoxysilane show similar mass distribution patterns. Meanwhile, corn starch, PFBS, chitosan, and trimethoxyphenylsilane display moderately lower mass but still remain environmentally significant. Notably, acetic acid and glycerol have the lowest environmental mass, indicating rapid degradation or limited intermedia transport capacity. In the case of emissions to natural soil, corn starch displays a total environmental mass approximately twice that of PFOA, with sodium alginate slightly exceeding PFOA's value. Methyltrimethoxysilane remains within a comparable range, while all other compounds including PFBS, chitosan, glycerol, and acetic acid, demonstrate substantially lower environmental persistence. Of particular interest, acetic acid and glycerol consistently exhibit the lowest total environmental mass across all emission scenarios, suggesting that they may be among the most environmentally benign alternatives to PFOA.

The behaviour of PFBS, while often regarded as a lower-impact short-chain PFAS, appears highly dependent on the emission scenario. Although it shows lower mass distribution in the emission to air and soil cases, its environmental persistence remains significant under seawater emission, indicating that chain length alone does not guarantee environmental safety. These simulations suggest that acetic acid and glycerol represent promising environmentally friendly alternatives to PFOA, given their minimal persistence and transport potential. However, it is essential to complement these multimedia fate assessments with toxicological evaluations, including bioaccumulation, ecotoxicity, and human health impact studies, to ensure their overall safety. The *SimpleBox4Planet* platform proves to be a valuable regulatory support tool, offering quantitative assessments of how chemical emissions influence environmental distribution, thereby aiding in the prevention, mitigation, and informed substitution of harmful substances within regulatory and industrial frameworks without the need for advanced mathematical skills.

3.4 Statistical significance of the physicochemical properties of PFOA

One of the key advantages of the *SimpleBox4Planet* platform is its capability to explore the impact of numerous emission and environmental scenarios with minimal manual effort. In this section, we leverage this capability to investigate the influence of physicochemical property variability on the total environmental mass distribution of PFOA, specifically following direct emissions to seawater at the continental scale, a scenario previously identified as producing the highest environmental burden. To systematically assess the sensitivity and significance of selected physicochemical parameters, a Plackett–Burman (DoE) design, a type of fractional factorial design that assumes interactions can be completely ignored and thus that the main effects can be calculated with a reduced number of experiments, was employed using the Isalos Data Analytics Platform.[87–89] A total of 20 experimental combinations were simulated based on the Plackett–Burman design that varied key properties within their defined minimum and maximum bounds (see Table 2). The physicochemical properties explored included the soil–water partition coefficient (K_{sw}), air–water partition coefficient (K_{aw}), octanol–water partition coefficient (K_{ow}), acid dissociation constant (pK_a), melting temperature (T_m), vapour pressure at 25 °C (P_{vap25}) and solubility at 25 °C (Sol25). The range of values

Table 2 Physicochemical properties (factors) and their corresponding minimum and maximum levels used in the Plackett–Burman design of experiments to evaluate their influence on the total environmental mass distribution of PFOA following direct emission to seawater at the continental scale

	T_m (°C)	pK_a	P_{vap25} (Pa)	Sol25 (mg L^{-1})	K_{aw}	K_{ow}	K_{sw}
Min	40	0	0.1	500	8.08×10^{-8}	83	1
Max	60	3.8	12	50 000	1.00×10^{-6}	3981	100

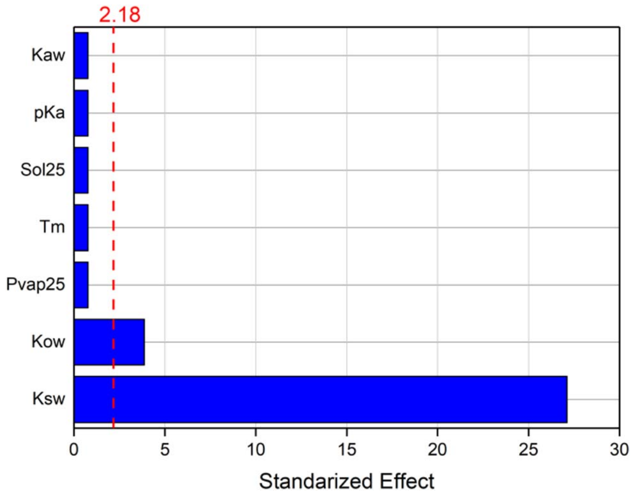


Fig. 14 Pareto chart illustrating the standardized effects of each physicochemical property on the total environmental mass distribution of PFOA following direct emission (1000 tonnes per year) to seawater at the continental scale, based on the Plackett–Burman screening design generated using the Isalos Data Analytics Platform. The dashed red vertical line represents the statistical significance threshold, indicating the minimum effect size required for a factor to be considered significant at the chosen confidence level.

Table 3 Analysis of variance (ANOVA) results for the Plackett–Burman design, evaluating the effect of each physicochemical property on the total environmental mass distribution of PFOA following direct emission (1000 tonnes per year) to seawater at the continental scale. The analysis was performed using the Isalos Data Analytics Platform, and the simulation outputs were generated using the *SimpleBox4Planet* web application. DF: degrees of freedom; SS: sum of squares; MS: mean square

	DF	Adjusted SS	Adjusted MS	*F*-Value	*P*-Value
T_m	1	50 041	50 041	0.60	0.453
pK_a	1	49 897	49 897	0.60	0.454
P_{vap25}	1	50 057	50 057	0.60	0.453
Sol25	1	49 955	49 955	0.60	0.454
K_{aw}	1	49 628	49 628	0.60	0.455
K_{ow}	1	1 250 255	1 250 255	15.00	0.002
K_{sw}	1	61 286 370	61 286 370	735.16	0.000

selected for each property reflects bounds relevant to PFOA's speciation, encompassing both its neutral and anionic forms.

Fig. 14 presents the Pareto analysis (the 80/20 rule to determine the strongest contributing factors), and Table 3 summarizes the results of the analysis of variance (ANOVA)-based regression modelling, both computed using the Isalos Data Analytics Platform based on simulation data generated by *SimpleBox4Planet* for the total mass of PFOA distributed across the environment (see Table S8 in the SI). It is important to note that the Pareto chart plays a prioritization role following the Pareto principle (80/20 rule), where the parameters (factors) whose cumulative contribution reaches approximately 80% variability are considered the most influential, whereas those contributing the remaining 20% are treated as less important. The red dotted threshold line in Fig. 14 visually marks this 80% cut-off, clearly distinguishing the dominant parameters, thereby identifying those factors that most strongly drive PFOA's environmental fate. Prior to discussing this statistical analysis, it is worth noting that the total environmental mass of PFOA distributed across compartments under the 20 Plackett–Burman design scenarios ranges narrowly from 675.49 tonnes to 679.49 tonnes. This illustrates that even modest changes within realistic ranges still yield consistently high environmental retention. This observation confirms that, while PFOA's distribution behaviour remains generally robust, small parameter variations can influence its multimedia fate and should not be overlooked. The results of the Pareto chart and ANOVA analysis both reveal that K_{sw}, the soil–water partition coefficient, has the most significant influence on the total environmental mass distribution of PFOA. Additionally, K_{ow} (the octanol–water partition coefficient) is identified as a statistically significant contributor. The rest of the physicochemical properties, including K_{aw}, P_{vap25}, Sol25, and T_m, are found not to be statistically important, within the tested parameter space. These findings underscore a critical modelling insight into the application of multimedia environmental fate models such as SimpleBox: the accurate specification of partition coefficients, particularly those governing water–soil and water–organic phase interactions, is critical to ensuring the reliability of model predictions. Given PFOA's strong intermedia mobility, hydrophilicity, and persistence, small inaccuracies in these parameters can propagate through simulations and meaningfully affect the outcomes. As such, great care should be taken when sourcing, estimating, or experimentally determining these properties during model setup, especially in the context of regulatory assessments or comparative evaluations of chemical alternatives.

4 Discussion and conclusion

This work presents the development and implementation of *SimpleBox4Planet*, a web-based environmental fate modelling tool that integrates the functionality of the SimpleBox 4.04 fugacity-based multimedia model within a user-friendly graphical interface and facilitates further analysis of factors driving environmental fate *via* Design of Experiments using the Isalos platform. *SimpleBox4Planet* is a freely accessible web application hosted on the Enalos Cloud platform (https://www.enaloscloud.novamechanics.com/proplanet/simplebox4planet/or https://www.enaloscloud.novamechanics.com/chiasma/simplebox4planet/), for quantifying the environmental fate and transport of chemical substances, demonstrated here *via* a case study on persistent and emerging pollutants such as per- and polyfluoroalkyl substances (PFASs) and their alternatives. The web application supports both steady-state and dynamic modelling, allowing users to investigate time-dependent chemical behaviour and fate factor computation. Through its incorporation of RESTful APIs and automated CAS-based property retrieval *via* the EPA CompTox Dashboard,[14] *SimpleBox4Planet* enhances FAIR compliance and ensures interoperability with other environmental and regulatory tools. Its comparative analysis capability further provides a decision-support mechanism for identifying more sustainable alternatives to persistent chemicals such as PFASs, thereby addressing urgent regulatory and public health challenges. Overall, in comparison to prior SimpleBox-based tools, such as SimpleBox,[5] SimpleBox4Nano[90] and SimpleBox4Plastic,[91] the *SimpleBox4Planet* web application eliminates the need for complex Excel workbooks and external R scripts by providing a single, browser-based platform that performs steady-state, quasi-dynamic, and fate-factor calculations. It enables fast, transparent parameterization through a clean, sectioned GUI, providing direct controls for emissions and landscape settings instead of multi-tab spreadsheets, and offers multi-scale visualization (regional, continental, and global zones) with clear tabular and graphical outputs. A PFAS baseline (~4000 substances) is included with physicochemical properties retrieved from CompTox to support comparative assessments of PFASs and non-PFAS alternatives. *SimpleBox4Planet* exposes REST APIs to integrate results into regulatory and SSbD workflows, which was not directly achievable in prior spreadsheet-based implementations.

The case study on PFOA presented in this work demonstrated the capability of *SimpleBox4Planet* in characterizing environmental distribution patterns across different emission scenarios in air, seawater and soil. Consistent with the literature,[40,79,82] PFOA showed high mobility and long-term persistence in aquatic systems, with dominant partitioning into coastal and deep ocean waters and a marked tendency for long-range transport toward arctic and moderate climatic zones. Dynamic simulations further verified the environmental persistence of PFOA, particularly in aqueous compartments, with coastal seawater exhibiting the highest residence times across all emission pathways. The comparative analysis of the proposed alternatives, including PFBS, chitosan, acetic acid, and glycerol, showed that fluorine-free alternatives such as acetic acid and glycerol exhibited significantly lower total environmental burdens than PFOA, providing new insights into environmentally preferable substitutes. Moreover, sensitivity analyses based on a Plackett–Burman design, facilitated through integration of *SimpleBox4Planet* and Isalos Analytics Platform, emphasized the critical influence of soil–water and octanol–water partition coefficients on overall environmental distribution, highlighting the importance of accurately defining key physicochemical parameters during fate modelling. Collectively, the findings validate *SimpleBox4Planet* as a scientifically robust and policy-relevant platform, with enhanced user-friendliness and extended analysis capabilities relative to SimpleBox, for supporting chemical safety assessments and regulatory decision-making.

Future work will focus on extending the platform's capabilities by coupling it with Life Cycle Impact Assessment (LCIA) frameworks such as USEtox[13,92] to facilitate comprehensive evaluations of both environmental and human health risks, bridging the gap between multimedia fate modelling and impact quantification. Such an integration has been demonstrated previously for modelling the environmental fate of nanomaterials (using SimpleBox4Nano), in which two main adaptations were made: (i) merging of the compartments of air and rain and (ii) accounting for the sum of the free, aggregated, and attached species in the receiving compartments, *via* which it was extended to estimate characterisation factors (CF) for nano-TiO_2 for the impact category of freshwater ecotoxicity in life cycle assessment (LCA).[92] To improve the parameterization process for chemical inputs, *SimpleBox4Planet* will be coupled with automated workflows that incorporate Quantitative Structure–Activity/Property Relationships (QSAR/QSPR), machine learning (ML) algorithms, and quantum mechanical (QM) computations.[57,93] This integrative approach will enable the rapid and accurate estimation of critical physicochemical properties (such as partition coefficients, degradation kinetics, solubilities, melting temperatures and vapor pressures), thereby increasing the model's predictive accuracy. The platform's scope will also be expanded to support the modelling of emerging contaminants, particularly engineered nanomaterials (ENMs) and micro- and nanoplastics (MNPs), using the existing extensions of SimpleBox for nanomaterials (SimpleBox4Nano),[90] and the web application of this, https://enaloscloud.novamechanics.com/nanosolveit/simplebox4nano/. These advances will collectively transform *SimpleBox4Planet* into a comprehensive, next-generation environmental fate modelling platform—capable of supporting regulatory compliance, and the development of safe and sustainable-by-design (SSbD) chemicals, materials, and products across their entire life cycles.

Author contributions

Conceptualization: D. M. and A. A.; methodology: D. M.; software: D. M., C. P., and A. T.; supervision: G. M., J. S., R. H., I. L., and A. A.; writing—original draft preparation: D. M.; writing—review and editing: D. M., C. P., D.-D. V., A. T., G. M., J. S., M. M., A. R., T. S., R. H., I. L., and A. A.; funding acquisition: J. S., A. R., T. S., R. H., I. L., and A. A.

Conflicts of interest

There are no conflicts to declare.

Data availability

Supplementary information (SI): comprehensive analysis of the outcomes generated by using the *SimpleBox4Planet* web-tool. See DOI: https://doi.org/10.1039/d5su00622h.

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