sustainability

MDPI

Article

Chemical Footprint as an Indicator of Health Impacts: The Case of Dioxins and Furans in Brazil

Biagio Fernando Giannetti [1,*], Fábio Sevegnani [1], Feni Agostinho [1], Cecília M. V. B. Almeida [1], Pedro Henrique Bolanho Simões [2] and Gengyuan Liu [3,4]

1 Graduation Program on Production Engineering, Paulista University, São Paulo 04026-002, Brazil
2 Lisam EcoAdvisor Systems, São Paulo 05319-000, Brazil
3 State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China
4 Beijing Engineering Research Center for Watershed Environmental Restoration and Integrated Ecological Regulation, Beijing 100875, China
* Correspondence: biafgian@unip.br

Abstract: Humans are exposed to several chemical substances during their regular daily activities that can be harmful even in low quantities. Accounting for the mass of a given released chemical may not be appropriate for the assessment of its toxicological impact. To overcome the lack of a systemic perspective of mass-based assessments, methods such as the chemical footprint (ChF) are an alternative to account for a given chemical's environmental and human toxicological impacts, a task that is considered essential in order to achieve the Agenda 2030 for sustainability. Among others, persistent organic pollutants (POP) should receive attention due to their high potential impact. Using the USEtox model to estimate indicators of human health impact, this study proposes an approach to calculate ChF for dioxins and furans and applies it to Brazil as a case study. The USEtox model quantifies human health impacts from the characterization of factors of a given chemical. Results show that ChF for dioxins and furans is approximately 620 DALY, representing a potential loss of 620 years of life in the Brazilian population. Social costs related to dioxins and furans emissions achieved USD 30 million, translating into monetary values not found in the existing literature. Besides highlighting the impacts of chemical emissions on the Brazilian population, this work contributes to the advances in methods for quantifying more appropriately such impacts beyond the exclusive use of mass units, in turn supporting sustainability-related public policies.

Keywords: chemical footprint; health impacts; dioxins; furans; USEtox

Citation: Giannetti, B.F.; Sevegnani, F.; Agostinho, F.; Almeida, C.M.V.B.; Simões, P.H.B.; Liu, G. Chemical Footprint as an Indicator of Health Impacts: The Case of Dioxins and Furans in Brazil. *Sustainability* **2023**, *15*, 5314. https://doi.org/10.3390/su15065314

Academic Editor: Irene Petrosillo

Received: 26 January 2023
Revised: 13 March 2023
Accepted: 14 March 2023
Published: 16 March 2023

1. Introduction

Hazardous chemical substances are used in various industrial applications as base components or additives for various industrialized products. Humans are constantly exposed to these substances while breathing polluted air or ingesting contaminated water and food, affecting their health and consequently their capacity for learning and working activities, in turn causing negative impacts on several sustainability-related issues. Exposure to chemical substances can occur through several routes, including inhalation, ingestion, and dermal contact. The impact caused to human health and to the environment by a chemical substance depends on its physical and chemical properties, the local or regional environmental concentration of the substance, and the distribution among different environmental compartments [1]. The effects of emissions of toxic compounds, such as dioxins and furans, have been proven to be harmful to health. Since the 1970s, a worldwide concern of the scientific community and governments has been the establishment of targets for the banning of these substances. Today there is growing attention by scientists and governments regarding the release of several compounds with high toxicological and ecotoxicological potentials. Environmental accounting methods, such as those from the footprint family, are important tools to measure the potential impacts of human activities on the biosphere. Wackernagel and Rees [2], proposed the ecological footprint, and from this first proposal, several other footprint approaches were derived, including the carbon footprint, water footprint, and chemical footprint (ChF).

Since ChF is a relatively new metric, there is no consensus among experts on its definition. For example, Li et al. [3] have pointed out that the ChF definition depends on the perspective of the study, presenting different definitions including those from a natural ecosystem perspective, an environmental space occupancy, and also from qualitative perspectives. The non-governmental organization chemicalfootprint.org [4] defines ChF as "the total mass of chemicals of high concern used by an event, organization, service, building, or product." This seems to be a more commercial approach, far away from a scientific basis, and that limits itself to quantifying the use of chemicals rather than considering their effects on humans or the natural environment or their environmental persistence. In scientific terms, the ChF should refer to a metric capable of synthesizing the results of risk assessments, with the potential to communicate risks in order to use them as indicators of environmental impacts, including those on human health. Several studies state that the ChF may indicate the potential risk imposed by hazardous chemicals at the level of products, organizations, or nations [5–7]. According to Panko and Hitchcock [8], ChF is an indicator of the potential risk caused by a product based on its chemical composition, the toxicological and ecotoxicological hazards of the ingredients, and the potential for human exposure during the product's life cycle. Konkel [9] defines ChF as the quantifying of hazardous components in a product's life cycle and the potential risks it poses to humans and ecosystems. In the light of the findings of Fang et al. [10], ChF is classified as an "emission footprint for inventory" as it estimates the flows emitted to the environment (air, water, and soil) in absolute terms, adding the mass (kilograms) of toxic substances.

The first framework for assessing the ChF was presented by Sala and Goralczyk [6], combining a lifecycle assessment approach with a human and environmental risk assessment. Despite the high degree of uncertainty and limitations of the proposed method, these authors claim that the resulting impact indicators allow for assessments at different levels, that is, products, economic sectors, and the economy as a whole, as well as in different geographical levels (city, region, nation, etc.). However, these authors emphasize the need for further research to interpret the results and estimate the carrying capacity and the exposure limits for chemical pollution. The main benefit of applying the ChF, especially when the results of the risk assessment are compared with the limits of the planet, is the possibility of integrating existing knowledge in order to identify the so-called "hot spots" and support integrated assessments in order to manage chemical products [6]. Comparing the calculated impact with planetary limits remains a challenge for scientists who calculate the ChF because there are a large number of variables and interactions in the definitions of limits for environmental pollution.

Another aspect that deserves attention is that, differently from the carbon footprint and water footprint methods, the ChF is based on the release of chemicals with very different characteristics and the distinctive potential to cause environmental and health impacts. Some chemicals are highly harmful, even in very small amounts. In this way, a critical question persists: is it enough to account for the released mass of a given chemical? Another critical issue is the lack of a precise number to seek the planetary physical–chemical boundaries for releasing a given chemical without causing danger to humans and to the planet itself [11]. The fact is that accounting for mass does not show a tangible result, and an impact-based assessment of the environment and human health may provide a more reliable and easy-to-understand metric.

To our knowledge, there are no published studies comparing the assessment of impacts on human health against planetary boundaries. The values of planetary boundaries for the main anthropogenic tensions as defined by Rockström et al. [12] do not include limits for chemical pollution. Advances in research on ChF as a sustainability-based indicator focusing on ecotoxicological impacts can be found, such as those carried out by

Bjørn et al. [5], Zijp et al. [7], and Posthuma et al. [13]. For these authors, the risk assessments included ecotoxicological impacts on freshwater and were measured by comparing the dilution capacity needed to prevent ecosystem damage. This is because the authors defined the ChF as the necessary dilution to prevent damage to freshwater ecosystems. The evaluation of impacts on human health is allied to ChF indicators in several studies, such as those of Roos and Peters [14], Sörme et al. [15] and Tarasova et al. [16]. The "Toxic Footprint" of cotton t-shirt manufacturing calculated by Roos and Peters [14] is based on toxicological and ecological impacts and is a forerunner of the ChF that was proposed by Sala and Goralczyk [6]. National-level estimates, such as the "First Steps Towards Sweden's Chemical Footprint" published by Sörme et al. [15], are typically hampered by a lack of data on the quantities of chemicals emitted. Therefore, although limited in scope, there are emission inventories of great value to researchers and policymakers who wish, for example, to estimate an aggregate national-level ChF. The authors estimated the potential toxicological and ecotoxicological impacts based on information from the Pollutant Emissions and Transfer Register (PETR). This method combines the amount of released chemical substances with the USEtox model's characterization factors (CFs), a scientific consensus model endorsed by the UNEP's lifecycle initiative [17] (usetox.org [18]) to estimate the ChF indicator.

The USEtox is a model capable of predicting the destination and exposure to chemicals in order to quantify the potential impacts of human toxicity and freshwater ecotoxicity from characterization factors [19]. The model is considered by experts to be the most appropriate for assessing toxicological impacts [20,21]. Rosenbaum et al. [21] affirm that multimedia assessment models, such as USEtox, can predict the impact of emissions by combining substance distributions among different environmental compartments and exposure routes. The estimation of health impacts is based on CFs that are specific to each substance and that combine exposure potential and toxicity [20]. Additionally, Watanabe [22] points out that integrating risk assessment into the ChF appears to be a powerful tool and an indispensable approach to risk assessment in the context of environmental sustainability.

All these findings suggest that ChF emerges as a method capable of being integrated with conventional risk assessment, introducing a holistic and predictive approach by linking local to global risks in a more explicit and quantifiable way. Integrating ChF into conventional approaches appears to be a powerful and indispensable approach to situating risk assessment in the context of environmental sustainability. For example, Tarasova et al. [16] presented the results of the integration of ChF with risk analysis in the environmental impact assessment of chemical products (more specifically mercury) in Russia. Their study demonstrated the high impact of mercury in soil and water due to its excessive concentration. According to Tarasova et al. [23], to avoid global problems related to the effects of chemicals, it is necessary to develop a new global and proactive approach to the identification and management of chemicals that could pose a threat to the entire planet.

Dioxins and furans are chemicals produced unintentionally, mainly due to incomplete combustion processes, but also as result of other manufacturing processes such as pesticides, and chlorinated substances, among others. Dioxins (polychlorinated dibenzo-p-dioxins—PCDD) and furans (polychlorinated dibenzofurans—PCDF) are listed under annex C in the Stockholm Convention and are part of the group of POPs that have a long residence time in the environment, a low rate of degradation and a high potential to cause harmful impacts to humans and the environment [24]. Based on the definition of Panko and Hitchcock [8], the ChF of dioxins and furans in Brazil represents the indicator of the potential risk caused by the emission of pollutants and by the toxicological dangers of chemical substances, considering the standard exposure of a population. On the other hand, these authors do not take ecotoxicological hazards and the carrying capacity of the environment into account. In this context, this approach is similar to the framework of Čuček et al. [25], in which the ChF is classified as a combined environmental, social, and economic footprint. Emissions of dioxins and furans in the environment directly affect the population's health, causing loss of quality of life in society and directly affecting several United Nations sustainable development goals. Research focusing on the monitoring and management of POPs has been supported by the United Nations because there is a direct alignment with the UN's Sustainable Development Goals (SDGs), most specifically SDGs 15, 9, 6, 17, 12, 3 and 14 (UN, Department of Economic and Social Affairs [26]). This highlights the importance of studies related to the emissions of dioxins and furans, because they are strongly aligned with the SDGs.

The scientific literature shows that research focusing on the toxicological impacts of dioxin and furan emissions is of major importance and that assessments based exclusively on the emitted amount of a given pollutant in terms of its mass lack a systemic perspective to better represent its toxicological potential to the environment and consequently to human health. Contributing to the achievement of the goals established by the UN Agenda 2030, this paper provides a new approach to calculating ChF using the USEtox model to overcome the shortcomings existing in the literature. To illustrate its operational advantages, the proposed approach is considered for the assessment of the impact on human health in Brazilian regions, focusing on the ChF of dioxins and furans as a case study. To give a better perspective of the social costs as well as the loss of quality of life, monetary values are attributed to ChF. The possible gains predicted by the implementation of actions to reduce the emission of POPs in Brazilian territory, provided by the national implementation plan (NIP) of the Convention of Stockholm are evaluated in monetary terms.

2. Methods

2.1. The USEtox Model and the Assessment of Toxicological Impacts: A Proposal

In general, the USEtox model translates the quantity released from a certain chemical substance into a potential impact on the environment through the application of CFs. For human toxicity, a midpoint indicator reflects the change in the probability of disease occurring during the lifetime due to exposure to a chemical substance. It is presented in comparative toxic units per kilogram (CTUh/kg), equivalent to the number of disease cases per kilogram of a chemical substance emitted (cases/kg). Similarly, a midpoint ecotoxicity indicator represents the potential of species affected per unit mass of substance emitted (PAFm^3 day/kg) and is presented in comparative equivalent toxic units (CTUe). The USEtox model is widely used to estimate health impacts without necessarily referring to the indicator as ChF. In this scenario, it is common to assess impacts based on the endpoint indicator, which estimates the extent of human health damage related to emissions. This calculation involves the application of a damage factor to cases of illness, this is expressed in comparative damage units (CDUh) equivalent to years of life lost due to premature death or disability per kilogram of a chemical substance emitted (DALY/kg).

The disability-adjusted life year (DALY) proposed by Murray and Lopez [27] is the metric used by the World Health Organization (WHO, [28]) to measure the burden of disease in studies related to the health status of populations. It is also the unit used by the USEtox model to express the result of the assessment in terms of potential impacts on human health. According to Gao et al. [29], using DALY units within the USEtox has advantages in quantifying and comparing risks arising from environmental pollution.

The USEtox model uses generic environmental configurations for all spatial scales to represent the movements, transformations, and changes in the mass of contaminants among the environmental compartments, which depend on the physicochemical characteristics of the modeled chemicals and the characteristics of the compartments considered for modeling in the standard USEtox region, version 2.01. The fraction of dioxins and furans absorbed by the organism is embedded in the USEtox model. The model allows identification of the main exposure pathways, such as inhalation, drinking water ingestion and food ingestion.

The 2,3,7,8-TetraCDD substance characterization factors obtained from the USEtox version 2.0 organic substances database were used in this study. Emissions to the air, water, and soil environmental compartments were considered emissions to continental air, continental freshwater, and continental natural soil, respectively. We considered the CFs of this substance to be exclusively the occurrences and effects of cancerous diseases, as shown in Table 1.

Table 1. Endpoint and midpoint human characterization factors for substance 2,3,7,8-TetraCDD (CAS 1746-01-6). USEtox 2.01 Rosenbaum et al. [30].

CF	Unit	Environmental Compartment		
		Continental Air	**Continental Freshwater**	**Natural Soil**
midpoint	cases/$kg_{released}$	35	146	16
endpoint	DALY/$kg_{released}$	402	1673	179

Figure 1 shows the main steps for the proposed ChF calculation and its conversion to monetary values expressing human health impacts. The midpoint and endpoint CFs were obtained from USEtox and were combined with data from the National Inventory of Sources of Dioxins and Furans, to calculate midpoint and endpoint ISs. The IS endpoint becomes the ChF value, which is multiplied by the VFs and result in the monetary value of the impact on human health. The next sections explain in detail all the calculation steps. At this point, it is possible to realize the novelty presented in this study, since this calculation is not found in the existing literature.

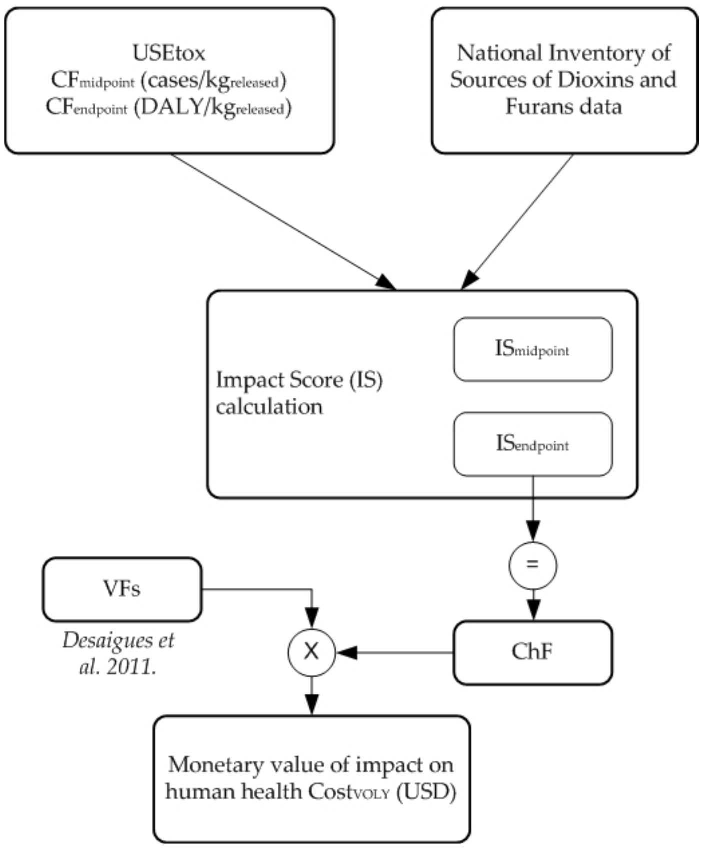

Figure 1. Schematic representation for the proposed ChF calculation and its monetary value for human health impacts [31].

2.1.1. Calculation of the Impact Score (IS)

The health risk assessment was calculated based on USEtox, which incorporates a database of CFs for human toxicity [30] and ecotoxicity for more than three thousand substances [19]. $CF_{midpoint}$ (cases/$kg_{released}$) considers potential disease occurrence, while $CF_{endpoint}$ (DALY/$kg_{released}$) considers the potential for damage to human life.

The impact score (IS) for human toxicity is calculated as the sum of the $CF_{mid/end}$ (midpoint or endpoint) of the environmental compartments (air, water and soil) multiplied by the mass of the substance released in each compartment [19], according to Equation (1).

$$IS_{mid/end} = \Sigma_i \Sigma_x CF_{mid/end\ x,i} \times m_{x,i} \quad (1)$$

where:

$IS_{mid/end}$ = impact score for human toxicity (mid/end depends on which CF is considered);

$CF_{mid/end\ x,i}$ = characterization factor (midpoint or endpoint) for human toxicity of substance x emitted to environment i; and

$m_{x,i}$ = mass of substance x emitted to environment i.

2.1.2. Calculation of the Chemical Footprint

The ChF is calculated from the $CF_{endpoint}$ ($DALY/kg_{released}$) obtained from the USEtox database, and from the estimate of the mass of chemical substances released for each environmental compartment during 2008 for each federal unit (FU) $m^{FU}_{x,i}$ ($kg_{released\text{-}2008}$), as shown in Equation (2). The endpoint impact score (IS_{end}) is then equivalent to the ChF. The measure of the impact score shows the potential of a certain amount of emissions to cause damage to the health of an exposed population.

$$ChF^{FU}_{2008} = \Sigma_i \Sigma_x CF_{endpoint\ x,i} \times m^{FU}_{x,i} \quad (2)$$

where:

ChF^{FU}_{2008} = chemical footprint for each FU in 2008 (DALY);

$CF_{endpoint\ x,i}$ = characterization factor (endpoint) for human toxicity of substance x emitted to environment i; and

$m^{FU}_{x,i}$ = mass of substance x released to environment i.

2.1.3. Monetary Valuation of Impacts on Human Health

The estimated cost of impacts is made by assigning monetary values to the calculated ChF. Monetary valuation is treated as an externality that can be positive when it produces benefits or negative when it represents costs or loss of well-being. According to Pizzol et al. [32], monetary valuation allows for the comparison of environmental impacts, which are usually measured in incomparable physical units, supporting easy-to-understand indicators for decisionmakers.

Valuation factors (VFs) recommended for new member countries of the European Union of € 33,000/value of a life year (VOLY) (USD 48,316/VOLY) [31] were considered in this study. One VOLY unit value is assumed to be equivalent to one DALY unit, and is related to the ChF of dioxins and furans as presented in Equation (3).

$$Cost^{FU}_{VOLY}(USD) = ChF^{FU}_{2008} \times VF_{VOLY} \quad (3)$$

where:

$Cost^{FU}_{VOLY}(USD)$ = cost of the release of dioxins and furans at each FU in 2008;

ChF^{FU}_{2008} = chemical footprint for each FU in 2008 (DALY); and

$VF_{VOLY}\,\frac{USD}{VOLY}$ = valuation factor.

The study of Desaigues et al. [31] focused on valuing the cost of losing a year of life, the so-called "intangible cost", that is, the amount of money that the population is willing to pay to extend their life expectancy by one year. The authors claim that VOLY is a key element for calculating the costs of damage caused by air pollution, representing the monetary value of one year of life.

2.2. Case Study

In order to show the advantages and how to apply the method, Brazil and its 27 FUs are considered as a case study. It is important to emphasize that the proposed approach can be applied to any other region in the world, depending exclusively on data availability. The methodology proposed by Sala and Goralczyk [6] was applied in the present case study to estimate the ChF of dioxins and furans, considering Brazil and its 27 FUs as spatial boundaries of the system.

The Brazilian inventory report is part of the national implementation plan for the Stockholm Convention launched by Brazil in 2015. This initiative manifests Brazil's international commitment to the Stockholm Convention and is an essential instrument for Brazil to mobilize resources to seek the eradication and reduction of POPs across its national territory. Based on data from 2008, the most updated official data source available, the Brazilian inventory report was published by the Ministry of Environment in 2013 [24] and followed the guidelines and emission factors of the second version of the standardized toolkit for identification and quantification of dioxin and furan releases [33].

The inventory results are segregated according to emission source categories and the distribution among Brazilian states and regions. Thermal and chemical industrial processes are the main sources of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD and PCDF). Emissions/releases are allocated into five compartments or media, as shown in Figure 2. The dashed line indicates the boundaries for collecting data from the inventory, the gray boxes are compartments that can contain dioxins and furans, and the boxes with bold tables represent steps in which these compounds can be generated.

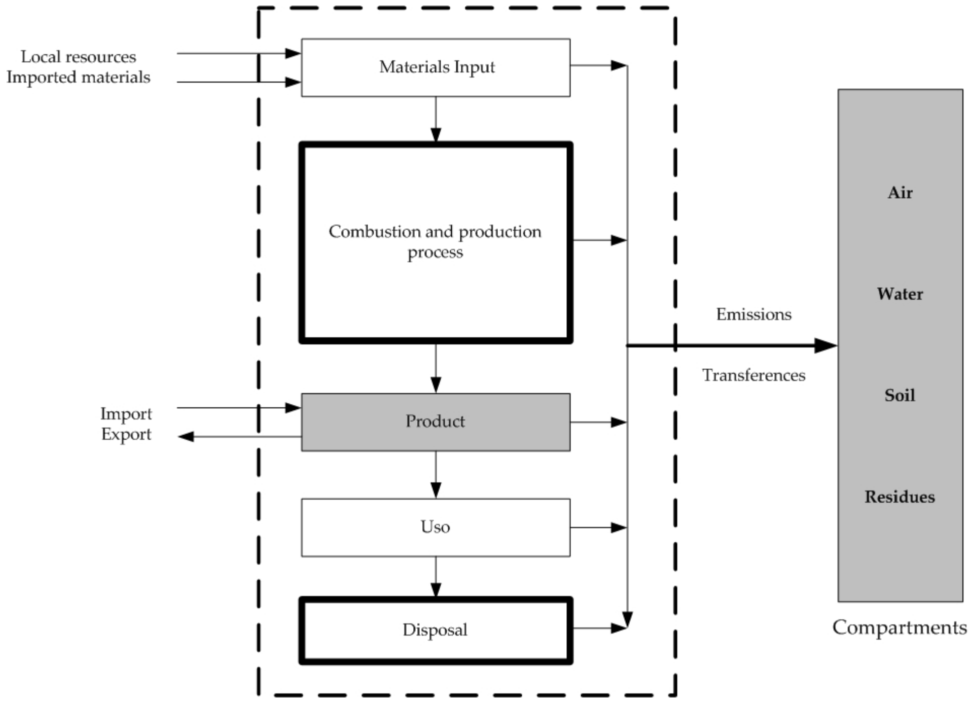

Figure 2. Lifecycle of dioxins and furans—Adapted from UNEP Chemicals [34].

The total amount of dioxins and furans estimated in Brazil for 2008 was 2235 grams of equivalent toxicity (gTEQ) [24], including emissions to air, water, soil, waste disposal, and products. This amount is presented in gTEQ, as this group of substances manifests as mixtures of 17 types of similar molecules acting collectively, and their potential toxicological effects are measured from the sum of their equivalent toxicity (∑TEQ) in relation to a more toxic congener called 2,3,7,8-TetraCDD [34].

To feed the USEtox risk assessment model with emissions data, information is reorganized so as to exclusively consider those emissions for the environmental compartments air, soil, and water. Two adjustments are necessary: disregarding releases in products and grouping the waste disposal with soil emissions. After this procedure, excluding the release of 419 gTEQ in products and adding the emissions of waste disposal and soil emissions, the total for dioxins and furans in Brazil is 1816 gTEQ distributed among the following environmental compartments: emissions to air (64.3%), soil (34.4%), and water (1.3%).

3. Results and Discussions

This section is presented in four parts for a better understanding of the proposed method applied to the Brazilian case study. First, are presented data for Brazilian emissions, followed by the ChF of the emission sources according to each environmental compartment. The ChF costs are presented next, as well as data regarding emissions reduction based on the Brazilian reduction plan. Finally, results are discussed, focusing on the advantages of the proposed method in assessing the health impacts on the population and the obtained cost reduction resulting from the applied actions of the national plan for emissions reduction, leading to social benefits, expressed as monetary values, and the consequent and major improvements towards sustainability.

3.1. Emissions of Dioxins and Furans

Based on the Brazilian national inventory [24], the total emission potential of dioxins and furans in Brazil for 2008 was 1816 gTEQ. The distribution of emissions by source category is shown in Table 2, presenting the amount released for each environmental compartment and the contribution of these emissions to the total quantity released.

Table 2. Mass emissions, by category of sources and means of release. Adapted from the Environment Ministry [24].

Emission Source Categories	Emissions of PCDD/PCDF				
	Air Water Soil gTEQ/yr			Total gTEQ/yr % kg/kg	
Waste incineration	72.8	0.0	38.7	111.5	6.1
Production of ferrous and non-ferrous metals	557.4	0.4	296.8	854.6	47.0
Heat and power generation	41.6	0.0	11.6	53.2	2.9
Production of non-metallic mineral products	54.4	0.0	7.2	61.6	3.4
Transports	8.3	0.0	0.0	8.3	0.5
Open burning	430	0.0	79	509	28.0
Production of chemicals and goods	2.7	10.5	21.3	34.5	1.9
Miscellaneous	0.9	0.0	2.7	3.6	0.2
Disposal of effluents and waste	0.0	12.1	168	180.1	9.9
Total	1168.1	23.0	625.3	1816.4	100.0

Emissions of dioxins and furans come mostly from combustion processes, and the largest part (64% kg/kg total) is released into the atmosphere (air). The main contribution comes from the industrial production of ferrous and non-ferrous metals, followed by open burning. These two sources combine to contribute up to 75% of the total emissions of dioxins and furans in Brazil. To our knowledge, there are no published data that could allow for comparisons of the obtained results with studies performed in other regions.

3.2. Chemical Footprint of Emission Sources

In order to calculate the ChF, the toxicological CFs of the substance 2,3,7,8-TetraCDD were applied for the standard USEtox's model scenario as shown in Table 1. Dioxins and furans emissions to air, water, and soil were considered to calculate the score of the impact on human health midpoint (potential for the occurrence of diseases) and endpoint (potential for the occurrence of damage). The impact score, calculated for the year 2008 for Brazil was 53.8 cases, corresponding to 619.7 DALY, as shown in Table 3.

Table 3. Emissions by environmental compartment for the base year 2008, with midpoint and endpoint impact scores.

Brazil	Environmental Compartment			Total
	Air	Water	Soil	
Emissions (gTEQ/yr)	1168.1	23.0	625.3	1816.4
Midpoint impact score (cases/yr)	40.8	3.3	9.7	53.8
Endpoint impact score (DALY/yr)	469.1	38.5	112.1	619.7

Values were calculated according to the procedure shown in Equation (1).

The ChF of the sources of emission of dioxins and furans are represented by the endpoint impact score (Table 4). The first three lines of Table 4 show the ChF of the three main emission source categories representing 83% of the total potential risk calculated for dioxins and furans in Brazil. Emissions from all sources of emission of dioxins and furans add up 1816 gTEQ, with 1168 gTEQ of emissions to air, 23 gTEQ to water and 625 gTEQ to soil, resulting in a ChF of 619.7 DALY (Tables 3 and 4). The distribution of the ChF of dioxins and furans in Brazil (Figure 3) shows that more than 80% of the estimated risk comes from emissions that occur in SP, MG, RJ, ES, PA, PR, MA and BA States. Emission sources in the state of SP contribute 29% of the ChF, followed by MG (15%), RJ (12%) and ES (8.1%).

Table 4. Chemical footprint of dioxins and furans according to the emission sources for the base year 2008.

Emission Sources	Chemical Footprint	
	(DALY/yr)	% kg/kg
Production of ferrous and non-ferrous metals	277.7	44.8
Open burning	186.9	30.2
Waste and waste disposal	50.4	8.1
Waste incineration	36.2	5.8
Production of non-metallic mineral products	23.1	3.7
Heat and power generation	18.8	3.0
Production of chemicals/consumer goods	22.5	3.6
Transport	3.3	0.5
Miscellaneous	0.8	0.1
Total	619.7	100.0

3.3. Chemical Footprint Costs and Emission Reduction Action Plan

The action plan to reduce POPs releases [35] is composed of a set of goals, objectives, and actions for reducing or eliminating POPs of unintended formation. The action plan describes the measures for best environmental practices and best available techniques applicable to each of the sources of emission of dioxins and furans with a focus on the sources of greater participation in the inventory. The NIP strategies focus on the eight main sources of emissions to air and the two main sources of emissions to water and aim to reduce 49% of emissions to air and 67% of emissions to water. During the five-year action plan period, a decrease of 576.1 gTEQ in air emissions and 15.4 gTEQ in water emissions is forecast. This reduction corresponds to 233 DALY for emissions to air (Table 5) and 26 DALY for emissions to water (Table 6).

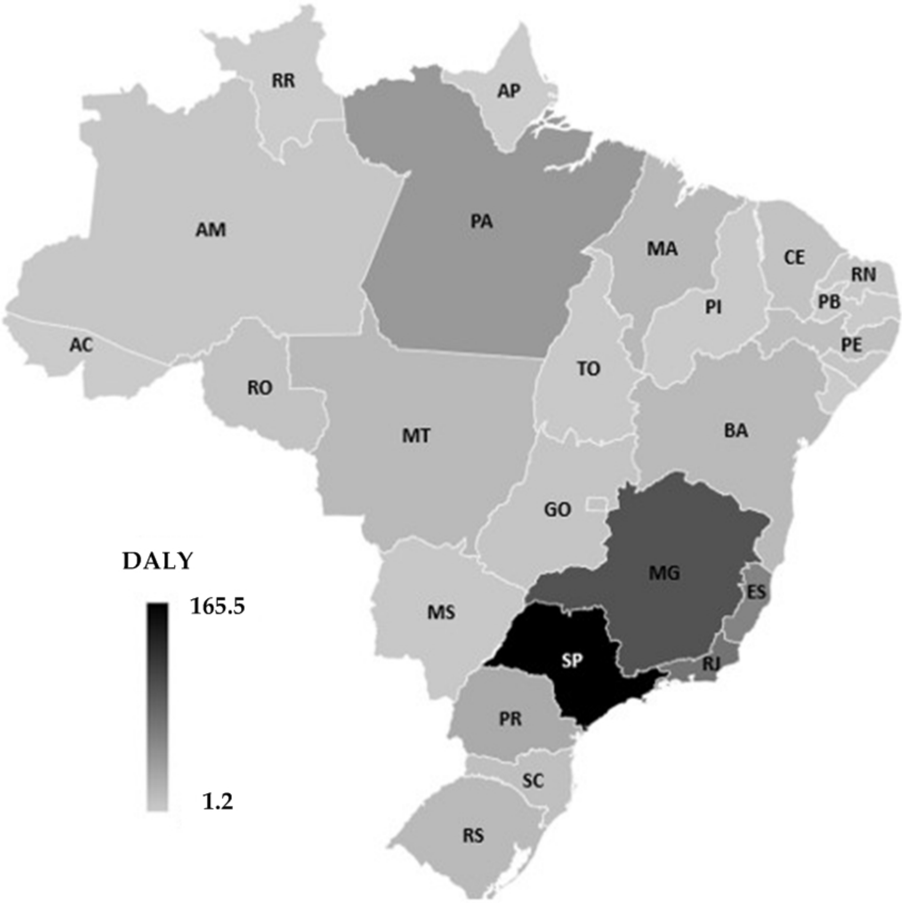

Figure 3. Distribution of the ChF of dioxins and furans in Brazil.

Table 5. Emission reduction forecast in the reduction plan: Emission sources to air.

Source (Subcategory)	Emissions to Air (gTEQ/yr)	% of Reduction kg/kg	Expected Reduction (gTEQ)	Expected Reduction (DALY)
Iron ore sintering	390.6	60.0	234.4	94
Outdoor burning biomass	300.2	50.0	150.1	60
Outdoor fire/waste burning	129.8	30.0	38.9	16
Incineration of health care waste	67.6	77.0	52.1	21
Iron/steel plants	57.9	51.0	29.5	14
Lime production	37.4	79.0	29.5	12
Aluminum production	28.1	84.0	23.6	9
Thermal recovery of electrical wires and cables	24.5	73.3	18.0	7
Total	1036.1	-	576.1	233

Table 6. Emission reduction forecast in the reduction plan: emission sources to water.

Source (Subcategory)	Emissions to Water (gTEQ/yr)	% of Reduction kg/kg	Expected Reduction (gTEQ)	Expected Reduction (DALY)
Pulp and paper production	10.1	91.0	9.2	16
Disposal of untreated effluents in surface water	9.9	63.0	6.2	10
Total	20	-	15.4	26

Besides the ability of the proposed model to allow the quantification of health impact by means of the ChF, it is also possible to convert it into monetary costs. The cost of the ChF of dioxins and furans refers to the "intangible cost" and is treated as an externality that represents the valuation of the loss of quality of life of the population and does not refer to the costs of medical and hospital expenses or other "direct" costs. This can be called a social cost because it represents the perceived monetary value that the population is disposed to pay in order to extend their life expectancy by one year. Besides others, the loss of quality of life leading to a lower life expectancy directly impacts SDG three. In Brazil, the estimated social cost of health impacts due to the population's exposure to dioxins and furans, for the base year 2008, is about US$ 30 million dollars. This value was calculated based on 619.7 years of life lost (DALY). The costs were estimated considering the loss of quality of life of the population due to exposure to dioxins and furans, according to Equation (3). The VOLY value of USD 48,316 was considered a conversion factor for transforming the estimated damages into monetary values. The amount of VOLY used for conversion represents the amount that a European citizen, on average, is willing to pay to extend life expectancy by one year; an amount that was calculated by Desaigues et al. [31] for new member countries of the European Union. This VOLY value was applied to calculate the costs of the ChF in Brazil and its states regardless of the per capita income. The ChF costs of the eight main federative units total USD 24 million, calculated based on the ChF of 499 DALY. The graph in Figure 4 shows the cost corresponding to each FU and its contribution to the total cost. Observing the Pareto curve in Figure 4 it is possible to infer that efforts towards the reduction in emissions of dioxins and furans in SP, MG and RJ would result in great improvement at the national level in Brazil.

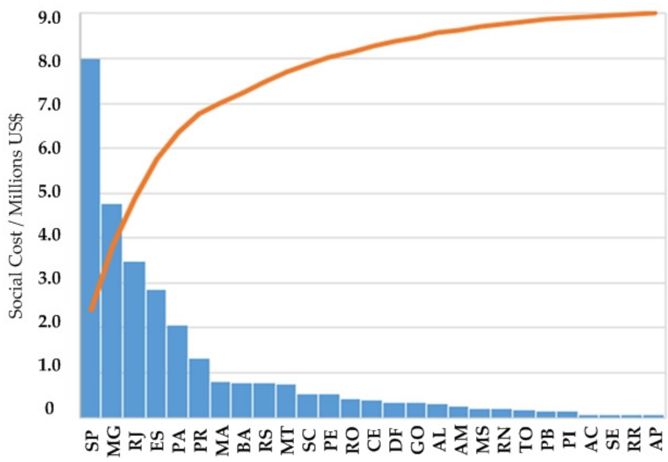

Figure 4. Cost of the ChF of dioxins and furans by FU.

The valuation of the environmental and human health impacts allows comparisons to be made on several other perspectives using monetary value, for example, in the cost–benefit analysis of the Emission Reduction Action Plan. The strategies of the Brazilian NIP, if implemented, would reduce 259 DALY during the action plan period. If the VF of US $ 48,316/DALY is applied, the benefit amount of this emission reduction is US $ 12.53 million, as shown in Table 7. One of the goals of the action plan to reduce POPs releases is to promote the application of measures to reduce or eliminate emissions of dioxins and furans, and raising the costs of these measures is an important action to achieve this goal. So far, in Brazil, little information is available on the forecast of implementation costs, but once raised, the implementation costs can be compared with the values calculated in a cost-benefit analysis.

Table 7. Reduction of emissions of dioxins and furans into the air according to subcategories of sources for the base year 2008.

Source (Subcategory)	Expected Reduction (DALY)	Social Benefit (USD)
Iron ore sintering	94	4,547,639
Outdoor burning biomass	60	2,912,616
Outdoor fire/waste burning	16	755,611
Incineration of health care waste	21	1,010,043
Iron/steel plants	14	673,938
Lime production	12	573,325
Aluminum production	9	458,024
Thermal recovery of electrical wires and cables	7	348,476
Pulp and paper production	16	743,129
Disposal of untreated effluents in surface water	10	504,287
Total	259	12,527,088

From Table 7, we can see that the three emission source categories that contributed most to human toxicity were the production of ferrous and non-ferrous metals, open burning, and disposal of effluents and waste. The results of the risk quantification reinforce the conclusions of the National Inventory of Sources of Dioxins and Furans [24] and the importance of prioritizing these sources as was done in the dioxins and furans reduction action plan of the Brazilian Ministry of Environment and in the NIP [35,36].

Studies on the assessment of impacts on human health, such as the study by Sörme et al. [15], have shown that the most significant contaminants for human health effects are not those of the greatest quantities. The present study confirms that the inclusion of toxicity and exposure scenarios in chemical risk assessments adds more reliability and precision to the results than assessments based exclusively on the mass of substances released.

Dioxins and furans, despite being a group of substances, are treated as a single substance in the risk assessment, as the emissions are quantified in relation to the equivalent toxicity of the most toxic branch of this group of substances. The risk modeling considers the physical–chemical properties of the substance 2,3,7,8-TetraCDD and the average characteristics of a standard fictitious region, considered as an environment model to predict the behavior of substances between environmental compartments, and estimates the average fraction ingested by humans and the potential damage from this intake.

Ideally, the USEtox parameters should consider the specific characteristics of the studied location. The USEtox model allows one to customize these parameters—area dimensions, temperature, and wind speed—but experts recommend the use of standard CFs as they reflect the average environmental characteristics of the environments [5].

Before the application of the CFs, it was not possible to add the emissions to water, air and soil. From the risk calculation, it was possible to represent the risk in a single value to establish a list of priorities among the categories of emission sources. This is a major achievement of this method. When comparing the contribution results of the emission sources, it was verified that there are variations between the representativeness of the emission sources when quantified in mass (% total kg/kg) and when it is considered using the risk calculation (% total DALY/DALY). For example, in the case of emissions from the production of ferrous and non-ferrous metals, the contribution varied from 47% to 44.8%, and from the emissions from the production of chemical products/consumer goods the contribution varied from 1.9% to 3.6% (Table 8).

The differences found between the mass quantity assessment and the risk assessment are due to the compartment that receives the release. The USEtox model considers emissions to water four times more harmful to health than emissions to air and ten times more harmful than emissions to the soil. This difference is evidenced in the CFs for human toxicity for the substance 2,3,7,8-TetraCDD, with the CF for water being 1673 DALY/$kg_{released}$, 402 DALY/$kg_{released}$ for air and 179 DALY/$kg_{released}$ for the soil. Despite being more harmful to health, emissions to water represent only 6% of the risk, and emissions to air remain the most representative, as it is the medium that receives the greatest amount of emissions (64%). In the comparison between Figures 5 and 6, there is an evident increase in the relevance of emissions to water and air in the distribution of total emissions in Brazil, as releases in these media have greater potential to be transferred to humans and to cause damage to health.

Table 8. Total mass emissions versus ChF. Emissions of dioxins and furans for the base year 2008, according to emission source categories.

Description	Air	Water (gTEQ/yr)	Soil	% Total kg/kg	% Total DALY/DALY
Production of ferrous and non-ferrous metals	557	0.4	296.8	47.0	44.8
Open burning	430	–	79.0	28.0	30.2
Waste and waste disposal	0	12.1	168.0	9.9	8.1
Waste incineration	73	–	38.7	6.1	5.8
Production of non-metallic mineral products	54	–	7.2	3.4	3.7
Production of chemicals/consumer goods	3	10.5	21.3	1.9	3.6
Heat and power generation	42	–	11.6	2.9	3.0
Miscellaneous	1	–	2.7	0.2	0.1
Transport	8	–	–	0.5	0.5
Total	1168.0	23.0	625.3	100.0	100.0

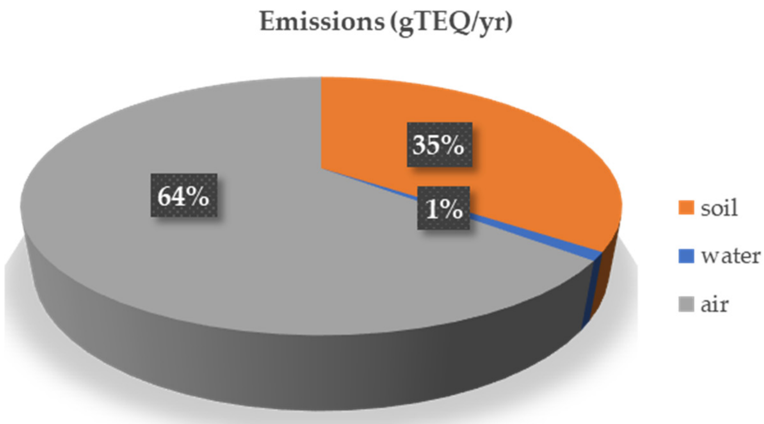

Figure 5. Quantity of emissions for each environmental compartment.

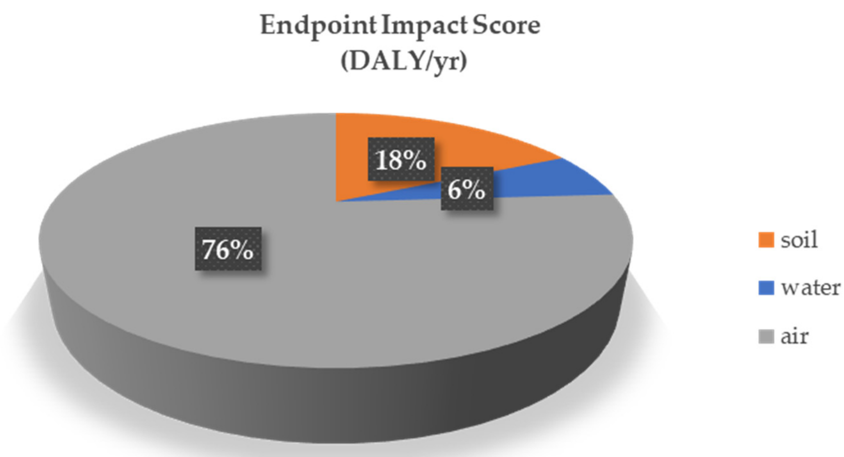

Figure 6. Distribution of risk between environmental compartments.

The largest ChF among the emission sources is the production of ferrous and non-ferrous metals. This category is subdivided into 12 activities (subcategories) and the most relevant for the ChF of dioxins and furans in Brazil is iron ore sintering, which contributes 26% of Brazil's total risk. This activity is part of the steel industry, more specifically, the integrated steel production line. In Brazil, there are 12 industries, located mainly in the southeast region, in the states of ES, MG, RJ, and SP [24]. The formation of dioxins and furans in the sintering process occurs due to the presence of chlorinated compounds during the synthesis process. Chlorinated compounds are present in greater quantity when sintering is done with contaminated raw material, waste and recyclable materials. The factors that most influence the amount of emission of dioxins and furans in the production process are the amount of waste, including cutting oils or other chlorinated contaminants in the raw material; the level of control of the combustion process; and the use of advanced technologies to control emissions of dioxins and furans. In this way, results obtained by this model show that this activity should receive special attention since it is a major contributor to the ChF of dioxins and furans.

The Brazilian inventory highlights high uncertainties in the emission estimates of these subcategories due to the framing of the emission sources. For the application of emission factors, the inventory classified 50% of Brazilian steelmakers as class 1 and 50% as class 2. The emission factors used to estimate the amount of dioxins and furans in class 1 steelmakers are four times greater than in class 2 [34]. Class 1 refers to installations without emission control and with a high amount of waste and contamination of raw materials and class 2 for steel plants with a low rate of waste use and with emission control.

In Brazil, steel production takes place on integrated steelmaking production lines in which the sinter is carried out at the steelworks itself, usually from coal and with emission control systems. In addition to integrated systems, there are also semi-integrated systems, called "pig iron makers", which use charcoal and often have less control over emissions. Due to the absence of emission factors for semi-integrated systems, the working group that prepared the inventory decided to classify these sources in class 1, however, it is expected that the emissions of this subcategory will be reviewed in future inventories [24].

The second main contributor to emissions of dioxins and furans is outdoor burning, with 21% of the ChF. This source includes bushfires, which occur mainly in the north and northeast regions, and the burning of sugarcane fields, concentrated in the state of SP and in the northeast region.

3.4. The Burden of Disease in the Population

Assuming that health damage occurs within the same geographic limits where emissions occur, it can be said that the ChF of dioxins and furans is approximately 620 DALY. This represents the potential loss, in Brazil, of 620 years of life due to diseases related to this group of substances, directly affecting several of the Agenda 2030 goals. The ChF metric provided by the model gives a clear and steady statement of the health impact caused by the emissions of dioxins and furans. The use of DALY as a metric for evaluating potential health impacts allows one to interpret the result of risk as the burden of disease (BOD) emissions of these substances. If we consider the damage distribution, 64% of the disease burden affects the population of the southeast, 11% in the northeast, 10% in the north, 9% in the south, and 6% in the Midwest. Among the Fus, the greatest burden of disease is in the population of São Paulo with 165.5 DALY/year, followed by MG 99.0 with DALY/year, RJ with 72.2 DALY/year, and ES 59.0 with DALY/year.

For dioxins and furans, the impacts are caused by very low amounts of emissions, and the uncertainties of the inventory can significantly influence the results. According to [5], emission inventories are important sources of uncertainty, especially for organic chemical substances, since there are no systems to monitor many of these degradation components and byproducts. The comparison between the emission inventories of different countries is minimized because the application of the toolkit guidelines occurs in a uniform way, that is, all users have access to the same emission factors [24]. Risk assessment is another important source of uncertainty and error found by Bjørn et al. [5], more precisely, this source of uncertainty resides in the inconsistency between the standard compartmental volumes assumed in the USEtox model to calculate the CFs. Despite these uncertainties, USEtox is the best existing tool and shows the greatest potential, for quantifying and assisting decision-makers with human and ecotoxicological impacts.

It Is worth pointing out that the application of the ChF makes it possible to measure and compare the impact on human health caused by several different chemical substances simultaneously, by converting all of them so that they can be compared on the same basis. However, as is typical for any existing model in the literature, chemical substances are considered individually instead of being blended to obtain a new or different substance with a different impact. This is not an exclusive limitation of the proposed model. Hauschild and Huijbregts [37] have presented several studies that corroborate this idea. The proposed approach in this study goes beyond the simple toxicity assessment because it includes the USEtox model to assess the exchange or mobility of each substance among the environmental compartments (air, soil and water), and its potential effects on human health. This can be considered an advancement of existing similar models for the achievement of higher accuracy.

3.5. Limitations and Suggestions for Future Works

One limitation of this study is that the amounts of released dioxins and furans proved to be relatively proportional to the estimated risks to human health. This is because the USEtox modeling was undertaken from a single group of substances. The most toxic branch in this group, 2,3,7,8-TetraCDD, was used as a reference for the calculation, so the variation is due only to the environmental compartment that receives the emission. As an attempt to overcome these limitations, future efforts should be made to expand the groups of substances. If other substances were part of this research, the potential impacts of the various substances could be added, and those with greater toxicity would be highlighted even if emitted in smaller quantities. Similarly, dioxin-like polychlorinated biphenyls were not considered due to the lack of a national inventory for this group of substances. These should be subject to future studies.

Accounting for the amount of imported water and food coming from other locations could enrich the model results as they approach the concept of methods called "footprints" but, due to lack of precise data, imported indirect impacts were not considered. The hypothetical inclusion of these data would involve compiling a large amount of information from specific geographic regions, which would make the model more accurate on a local scale, but not suitable to be replicated generically on a global scale. This limitation could be understood as a customization for future works.

Finally, the influence of external pollutants coming from abroad into the Brazilian territory was not considered. The amount of dioxins and furans migrating to, or coming from, other locations could have a significant impact on the results, and is something we suggest for future works.

4. Conclusions

The proposed model was applied to Brazil and its federal units (Fus), revealing the great potential for reduction in dioxins and furans emissions, which would contribute to the achievement of the goals of Agenda 2030. The hot spots for emissions in Brazil were identified by focusing on industrial activities and the specific Fus as well as the occurrence of diseases and premature deaths related to the exposure of the population. The obtained results allow the visualization of specific and focused policies toward the reduction of dioxins and furans emissions. The proposed model could be applied on a national basis to any other region, depending on data availability.

The ChF of dioxins and furans in Brazil has led to an estimated 620-year loss (DALY) at the cost of nearly 30 million dollars, affecting Brazilian efforts in achieving the UN SDGs. The comparison between the states showed that more than 80% of the estimated risk originates from eight of twenty-seven Fus, and that three emission sources are responsible for 83% of the total potential risk calculated for dioxins and furans in Brazil.

The ChF assessment identified the states (SP, RJ, MG and ES) where the population is most likely to suffer from the effects of exposure to dioxins and furans. This result represents a possibility to order the categories of emission sources that can assist in decision-making in public policies in the area of health and environment, such as the implementation of actions of the Stockholm Convention.

Results reveal, from a different quantitative approach, the importance of reducing the emission of dioxins and furans for better environmental and human health. Quantifying these impacts allows more effective public policies aligned to the UN SDGs. Specifically, SDG three (ensure healthy lives and promote well-being for all at all ages) is directly related to policies for dioxin and furan emission reduction to avoid the current Brazilian life quality loss of 620 DALY. SDGs six and nine also deserve attention, since dioxins and furans can be released into water bodies, and that both pollutants are mainly emitted by industrial activities. It is worth mentioning that NIP is a powerful environment policy that, if implemented accordingly, would allow a 259-DALY reduction in Brazil. This shows how relevant this work is towards sustainability enhancements.

Given the importance of the subject, further research is necessary to expand the scope of chemical substances, adding ecotoxicological impacts and including an assessment of the social costs of these impacts.

Author Contributions: Conceptualization, B.F.G. and P.H.B.S.; methodology, F.S. and F.A.; formal analysis, C.M.V.B.A. and G.L.; investigation, F.S. and P.H.B.S.; data curation, F.S. and P.H.B.S.; writing—original draft preparation, F.S., F.A. and P.H.B.S.; writing—review and editing, F.S. and F.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior-Brasil (CAPES) grant number 001 and CNPq Brazil grant number 302592/2019-9.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful for the financial support received from Vice-Reitoria de Pós Graduação da Universidade Paulista (UNIP). PHBS is grateful to the scholarship provided by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior-Brasil (CAPES-Finance Code 001). FA is grateful for the financial support provided by CNPq Brazil (302592/2019-9).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hester, R.E.; Harrison, R.M. *Chemicals in the Environment: Assessing and Managing Risk. Issues in Environmental Science and Technology*; Royal Society of Chemistry: London, UK, 2006; p. 158.
2. Wackernagel, M.; Rees, W.E. *Our Ecological Footprint: Reducing Human Impact on the Earth*; New Society Publishers: Philadelphia, PA, USA; Gabriola Island, BC, USA, 1996; p. 160.
3. Li, Y.; Cheng, Y.; Zhou, L.; Yang, Y. Advances, Norms, and Perspectives in Product Chemical Footprint Research. *Int. J. Environ. Res. Public Health* **2021**, *18*, 2728. [CrossRef] [PubMed]
4. The Chemical Footprint Project. Available online: chemicalfootprint.org (accessed on 12 December 2022).
5. Bjørn, A.; Diamond, M.; Birkved, M.; Hauschild, M.Z. Chemical Footprint method for improved communication of freshwater ecotoxicity impacts in the context of ecological limits. *Environ. Sci. Technol.* **2014**, *48*, 13253–13262. [CrossRef]
6. Sala, S.; Goralczyk, M. Chemical footprint: A methodological framework for bridging life cycle assessment and planetary boundaries for chemical pollution. *Integr. Environ. Assess. Manag.* **2013**, *9*, 623–632. [CrossRef] [PubMed]
7. Zijp, M.C.; Posthuma, L.; van de Meent, D. Definition and applications of a versatile chemical pollution footprint methodology. *Environ. Sci. Technol.* **2014**, *48*, 10588–10597. [CrossRef] [PubMed]
8. Panko, J.; Hitchcock, K. *Chemical Footprint Ensuring Product Sustainability*; Air & Waste Management Association: Pittsburgh, PA, USA, 2011; pp. 11–15.
9. Konkel, L. Chemical footprinting identifying hidden liabilities in manufacturing consumer products. *Environ. Health Perspect.* **2015**, *123*, 130–133. [CrossRef] [PubMed]
10. Fang, K.; Song, S.; Heijungs, R.; de Groot, S.; Dong, L.; Song, J.; Wiloso, E.I. The footprint's fingerprint: On the classification of the footprint family. *Curr. Opin. Environ. Sustain.* **2016**, *23*, 54–62. [CrossRef]

11. Persson, L.; Almroth, B.M.C.; Collins, C.D.; Cornell, S.; de Wit, C.A.; Diamond, M.L.; Fantke, P.; Hassellöv, M.; MacLeod, M.; Ryberg, M.W.; et al. Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. *Environ. Sci. Technol.* **2022**, *56*, 1510–1521. [CrossRef]
12. Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin III, F.S. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecol. Soc.* **2009**, *14*, 32. Available online: http://www.ecologyandsociety.org/vol14/iss2/art32/ (accessed on 15 December 2022). [CrossRef]
13. Posthuma, L.; Bjørn, A.; Zijp, M.C.; Birkved, M.; Diamond, M.L.; Hauschild, M.Z.; Huijbregts, M.A.J.; Mulder, C.; Van de Meent, D. Beyond Safe Operating Space: Finding Chemical Footprinting Feasible. *Environ. Sci. Technol.* **2014**, *48*, 6057–6059. [CrossRef]
14. Roos, S.; Peters, G.M. Three methods for strategic product toxicity assessment—The case of the cotton T-shirt. *Int. J. Life Cycle Assess.* **2015**, *20*, 903–912. [CrossRef]
15. Sörme, L.; Palm, V.; Finnveden, G. Using E-PRTR data on point source emissions to air and water—First steps towards a national chemical footprint. *Environ. Impact Assess. Rev.* **2016**, *56*, 102–112. [CrossRef]
16. Tarasova, N.P.; Makarova, A.S.; Vinokurov, S.F.; Kuznetsov, V.A.; Shlyakhov, P.I. Green chemistry and sustainable development: Approaches to chemical footprint analysis. *Pure Appl. Chem.* **2018**, *90*, 143–155. [CrossRef]
17. UNEP's Life Cycle Initiative. Available online: lifecycleinitiative.org (accessed on 15 December 2022).
18. USEtox. Available online: usetox.org (accessed on 20 November 2022).
19. Fantke, P.; Bijster, M.; Guignard, C.; Hauschild, M.Z.; Huijbregts, M.; Jolliet, O.; Kounina, A.; Magaud, V.; Margni, M.; McKone, T.; et al. *USEtox®2.0 Documentation (Version 1.1)*; USEtox®Team: Lyngby, Denmark, 2017. [CrossRef]
20. Hauschild, M.Z. Assessing Environmental Impacts in a Life-Cycle Perspective. *Environ. Sci. Technol.* **2005**, *39*, 81A–88A. [CrossRef] [PubMed]
21. Rosenbaum, R.K.; Bachmann, T.M.; Gold, L.S.; Huijbregts, M.A.; Jolliet, O.; Juraske, R.; Koehler, A.; Larsen, H.F.; MacLeod, M.; Margni, M.; et al. USEtox—The UNEP-SETAC toxicity model: Recommended characterization factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *Int. J. Life Cycle Assess.* **2008**, *13*, 532. [CrossRef]
22. Watanabe, C. Behavioral aspects of chemical use: Balancing an intrinsic conflict. *Curr. Opin. Environ. Sustain.* **2017**, *25*, 84–89. [CrossRef]
23. Tarasova, N.; Makarova, A.; Fantke, P.; Shlyakhov, P. Estimating chemical footprint: Contamination with mercury and its compounds. *Pure Appl. Chem.* **2018**, *90*, 857–868. [CrossRef]
24. United Nations Environment Programme—Stockholm Convention. Available online: http://www.pops.int/TheConvention/ThePOPs/AllPOPs/tabid/2509/Default.aspx. (accessed on 1 March 2023).
25. Čuček, L.; Klemeš, J.J.; Kravanja, Z. A Review of Footprint analysis tools for monitoring impacts on sustainability. *J. Clean. Prod.* **2012**, *34*, 9–20. [CrossRef]
26. United Nations Department of Economic and Social Affairs. Monitoring and Management of Persistent Organic Pollutants (POPs) in Asia. Available online: https://sdgs.un.org/partnerships/monitoring-and-management-persistent-organic-pollutants-pops-asia. (accessed on 1 January 2023).
27. Murray, C.J.L.; Lopez, D.A. (Eds.) *The Global Burden of Disease: A Comprehensive Assessment of Mortality and Disability from Diseases, Injuries, and Risk Factors in 1990 and Projected to 2020: Summary*; Harvard School of Public Health [u.a.]: Cambridge, MA, USA, 1996; p. 43. Available online: https://apps.who.int/iris/handle/10665/41864 (accessed on 1 November 2022).
28. World Health Organization. Available online: https://www.who.int/ (accessed on 25 September 2022).
29. Gao, T.; Wang, X.C.; Chen, R.; Ngo, H.H.; Guo, W. Disability adjusted life year (DALY): A useful tool for quantitative assessment of environmental pollution. *Sci. Total Environ.* **2015**, *511*, 268–287. [CrossRef]
30. Rosenbaum, R.K.; Huijbregts, M.A.J.; Henderson, A.D.; Margni, M.; McKone, T.E.; van de Meent, D.; Hauschild, M.Z.; Shaked, S.; Li, D.S.; Gold, L.S.; et al. USEtox human exposure and toxicity factors for comparative assessment of toxic emissions in life cycle analysis: Sensitivity to key chemical properties. *Int. J. Life Cycle Assess.* **2011**, *16*, 710–727. [CrossRef]
31. Desaigues, B.; Ami, D.; Bartczak, A.; Braun-Kohlová, M.; Chilton, S.; Czajkowski, M.; Farreras, V.; Hunt, A.; Hutchison, M.; Jeanrenaud, C.; et al. Economic valuation of air pollution mortality: A 9-country contingent valuation survey of value of a life year (VOLY). *Ecol. Ind.* **2011**, *11*, 902–910. [CrossRef]
32. Pizzol, M.; Weidema, B.; Brandão, M.; Osset, P. Monetary valuation in Life Cycle Assessment: A review. *J. Clean. Prod.* **2015**, *86*, 170–179. [CrossRef]
33. United Nations Environment Program—UNEP. Standardized Toolkit for Identification and Quantification of Dioxin and Furans Releases. 2005. Available online: https://wedocs.unep.org/bitstream/handle/20.500.11822/32443/STIQDFR.pdf?sequence=1&isAllowed=y (accessed on 1 September 2022).
34. Jones, K.C.; de Voogt, P. Persistent organic pollutants (POPs): State of the science. *Environ. Pollut.* **1999**, *100*, 209–221. [CrossRef] [PubMed]
35. Environment Ministry. Plano de Ação para a Redução Progressiva das Liberações de Poluentes Orgânicos Persistentes de Formação não Intencional (u-POPs). Convenção de Estocolmo. Brasília. 2015. Available online: http://www.mma.gov.br/images/arquivo/80037/Convencao%20de%20Estocolmo/Plano%20de%20Acao/Plano_nao%20intencional_prof%20assuncao_impressao_6_8_2015%20-%20finalissimos.pdf (accessed on 1 March 2018).

36. Environment Ministry. Plano Nacional de Implementação Brasil: Convenção de Estocolmo/Ministério do Meio Ambiente. Brasília: MMA. 2015. Available online: https://antigo.mma.gov.br/clima/convencao-das-nacoes-unidas/itemlist/category/113-convencao-de-estocolmo-poluentes-organicos-persistentes.html (accessed on 1 March 2018).
37. Hauschild, M.Z.; Huijbregts, M.A.J. (Eds.) *LCA Compendium—The Complete World of Life Cycle Assessment*; Springer: Dordrecht, The Netherlands, 2015. [CrossRef]