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Are melamine flame retardants in sofas beneficial from a life cycle perspective?

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Flame retardants (FRs) are added to sofas to save lives by improving fire safety. However, increasing concerns about the toxicity of FRs make it relevant to evaluate their net impacts. This study presents a methodological approach for comparing products with and without FRs based on life cycle assessment (LCA) and incorporating quantitative health risk assessment. Sofas with and without melamine FRs are compared, considering environmental and health impacts from cradle to grave. The assessment considered 19 midpoint categories and human health as an endpoint category (measured in disability-adjusted life years). For the midpoint-level LCA results, the main contributing processes are the production of the wooden sofa frame, followed by the polyurethane foam, and then the sofa's waste treatment. The contribution of the melamine FR to the overall impact is small, mainly due to the low quantity used (approximately 4.4% of the sofa's weight) and the relatively low toxicity of melamine. The avoided relative health impact from fire-related fatalities is larger than the health impact from melamine FR emissions. As a result, the net human health impact is lower for the sofa with melamine FRs. This approach provides a clearer understanding of the trade-offs involved in using FRs in furniture.

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Sustainability spotlight

To achieve a transition toward a non-toxic environment, it is relevant to quantitatively evaluate whether the use of toxic chemicals in products provides an overall benefit compared to not using them. This is particularly relevant for flame retardants (FRs), which are added to consumer products to improve fire safety, but also increase toxic emissions. Conventional LCA toxicity calculations typically consider only toxic emissions over the product life cycle, ignoring positive, life-saving effects. This study addresses this gap by extending conventional LCA through the integration of quantitative health risk assessment (QRA) to estimate reductions in fire-related fatalities. It therefore contributes to SDG 3 about good health and well-being and SDG 12 about responsible consumption and production, but also the environmentally related SDGs 13, 14 and 15.

Introduction

A flame retardant (FR) is an additive that aims to inhibit, suppress or delay an ignition to provide varying degrees of flammability protection.¹ The main types of FRs are brominated, chlorinated, phosphorus-based, nitrogen-containing, and inorganic FRs.² The ability of FRs to provide fire safety, coupled with increasing fire safety requirements, has led to their widespread use. This use has resulted in higher concentrations of FRs in the environment and increased human exposure.^{2,3} Their toxicity has raised concerns about the negative impacts of FRs on human health and the environment.^{4,5} These concerns are exacerbated by the limited knowledge about their long-term effects.⁶ Some FRs have also been classified as persistent, bioaccumulative and toxic.⁷ The Stockholm

Convention and other initiatives worldwide advocate phasing-out of legacy brominated FRs to prevent further toxicity impacts.⁸

Among FRs, melamine-based FRs are nitrogen-containing FRs that are widely used in various applications due to their effectiveness and halogen-free structure.⁹ Recently, a proposal to classify melamine as a substance of very high concern (SVHC) was submitted due to its persistent, mobile and toxic (PMT) properties, leading to its addition to the REACH Candidate List.¹⁰ This obliges producers and suppliers to provide users with health information and puts industry on notice about the likelihood of melamine being further restricted by inclusion in Annex 14 of the REACH regulation.

This said, FRs also bring useful functionality to products.^{11,12} Steen-Hansen and Kristoffersen¹³ analyzed fire statistics in buildings and concluded that incendiary fires often start in furniture. In addition, data on fatal fires shows that fires starting in upholstered furniture pose a high fatality risk.^{14,15} Non-flame-retarded polyurethane foam in upholstered furniture poses a significant fire hazard and has been identified as one of the largest fuel loads in residential fires, potentially leading to

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the loss of an entire home if not contained.^{16–20} FRs are therefore used in polyurethane furniture to prevent fires and the associated hazardous emissions.^{21,22} This led to the conclusion that fire-safe furniture is an effective fire countermeasure in both public areas and private homes.¹³ Such insights have led to the establishment of flammability standards.²³ Products used in buildings often have fire performance requirements regarding ignitability, flame spread, and heat release.¹⁵ The regulatory requirements for upholstered furniture are defined nationally, resulting in varying safety levels across Europe.²⁴ Today, the debate about furniture fire safety revolves around the risks associated with using toxic substances, such as halogenated FRs, to meet fire safety requirements,^{4,25} or to identify safer fire retardant systems with or without FRs.

Given that FRs can have both benefits and negative impacts on human health and the environment, an interesting question is how to evaluate the net impact of FRs? Most studies on FRs focus only on chemical hazards, potential exposure, and alternative substitutes.² A broader perspective that considers the entire life cycle of FRs within products, as well as the benefits they bring, might generate valuable insights. Life cycle assessment (LCA) is a method that can evaluate the potential environmental and health impacts over the product life cycle and relate them to the function of the product.^{26,27} LCA has previously been applied to FRs in products such as TV sets,²⁸ printed circuit boards,²⁹ laptops,²⁹ and fabrics.^{12,30} However, many LCAs involving FRs have been screening or simplified regarding the environmental impacts of FRs to reduce the time and resources required compared to a more complete LCA.³¹ Relatedly, specific methodologies for fires have been developed, such as the fire-LCA model.³² This model also includes the consequences of fire, *e.g.*, replacement of products damaged by fire, fire extinguishing, decontamination, and other consequences otherwise not considered in conventional LCA.³³ The fire-LCA model has previously been applied by Simonson, Tullin²⁸ to incorporate fire-related impacts into their assessments. However, their analysis of risks of different emissions did not extend to human health endpoints as currently calculated in LCA. Relatedly, these studies do not account for human health impacts that arise from other impact categories, such as climate change.

Considering the relevance of evaluating net impacts of FRs, this study has two aims. The first is to compare the potential environmental impacts of using FRs to not using FRs. The second is to compare the human health impacts of using FRs to not using FRs. These aims are addressed by an attributional LCA, with impacts considered at the midpoint level (*e.g.*, climate change, acidification and water use) for the first aim, and health impacts considered at the endpoint level (in terms of disability-adjusted life years, DALY) for the second aim. Traditional LCA calculations are extended by incorporating the results of a quantitative health risk assessment of fatalities due to fire. A sofa is considered as an illustrative case of a product containing FRs, specifically the FR melamine. To this end, we calculate and apply updated toxicity characterization factors (CFs) for melamine. The study also includes a sensitivity analysis regarding different levels of melamine exposure, allocation approaches, and end-of-life (EoL) scenarios to determine the range of LCA results under

different conditions. The key intended audience is policymakers involved in the regulation of FRs in products such as sofas. We also target the community of sustainability assessment scholars by providing another case of comparing positive and negative health impacts of products, as previously performed by, *e.g.*, Baumann, Arvidsson³⁴ and Furberg, Arvidsson.³⁵

Methods

This study follows the four steps of the LCA framework. We therefore describe the method under subheadings of goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation.

Goal and scope definition

This is a curiosity-driven LCA with the goal of exploring an approach to fulfilling the aims presented in the Introduction section. The functional unit is defined as the provision of sofa seating for one household over 10 years, with a reference flow of one sofa. The sofa considered is a typical three-seater sofa with inputs from global material markets. The life cycle includes raw material extraction, manufacturing, use within a residential building for a design life of 10 years, and EoL with incineration after use (Fig. 1). The use phase is assumed to occur in Sweden, which has implications for the EoL modeling. A comparison is made between a sofa impregnated with melamine FR and one without FR.

Life cycle inventory analysis

The primary data on the composition of the sofa is collected from the website of the furniture company IKEA, and from literature about furniture as described below. Data validity is ensured through cross-referencing with similar product specifications. The three-seater sofa consists mainly of two seat cushions and two back cushions made of polyurethane (PU) foam covered with synthetic leather, a bottom frame made of wood covered with 1 cm thick PU foams and 2 mm thick synthetic leather, two armrest frames made of wood covered with 1 cm thick PU foams and 2 mm thick synthetic leather, and four bottom acrylonitrile butadiene styrene (ABS) plastic stands. Additionally, the sofa contains screws and springs made of stainless steel. Fig. 2 shows a schematic illustration of the composition and dimensions of the three-seater sofa.

The manufacturing of the sofa as given in Table 1 includes the input of PU synthetic leather, covering a total surface area of 16.93 m² with a thickness of 2 mm and a surface density of 268 g m⁻². The synthetic leather is composed of 50% polyethylene terephthalate granulate and 50% flexible PU foam by weight. When melamine FR is added to the PU leather, it displaces 30% of the material's weight.^{36,37} The energy inputs, including electricity and heat for the production of PU-based synthetic leather, is included in Table 1 based on Sandin, Roos.³⁸ The sofa frame is made of wooden components with a total volume of 0.089 m³, a thickness of 1 cm, and a wood density of 529 kg m⁻³. The sofa includes four bottom stands made of ABS plastic, each cylindrical in shape with a radius of 2.5 cm and a height of 3 cm.



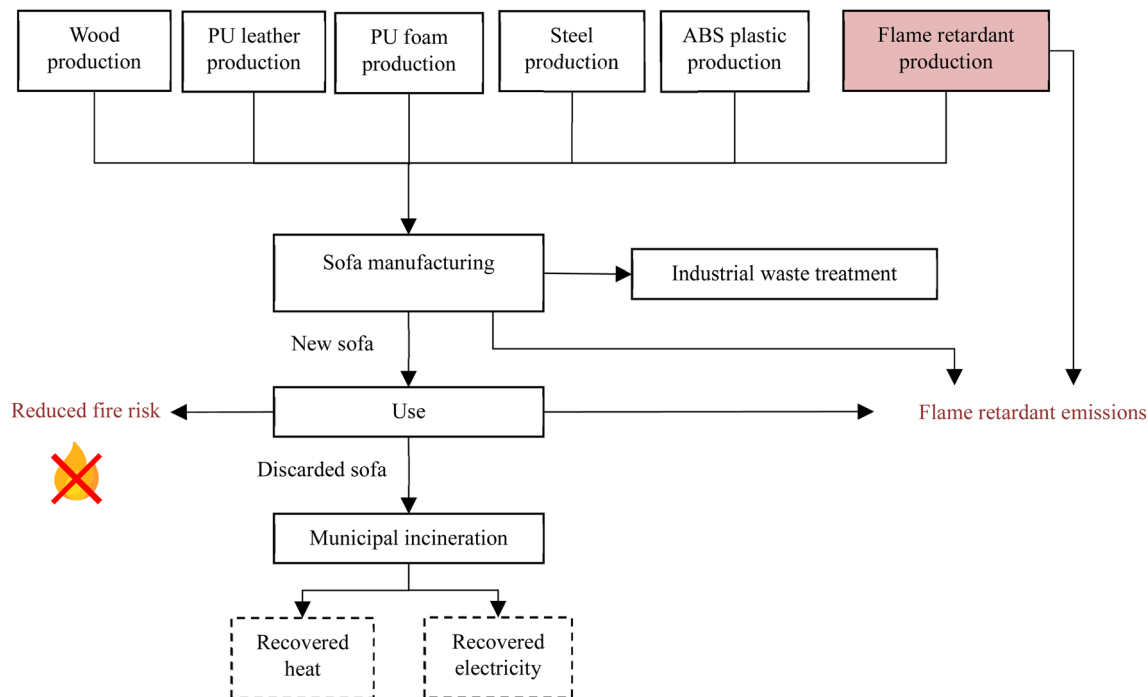


Fig. 1 Flow chart showing the life cycle stages of a sofa with and without flame retardant (FR). The FR-specific process is shown in red color and substituted processes in dashed boxes. PU = polyurethane, ABS = acrylonitrile butadiene styrene.

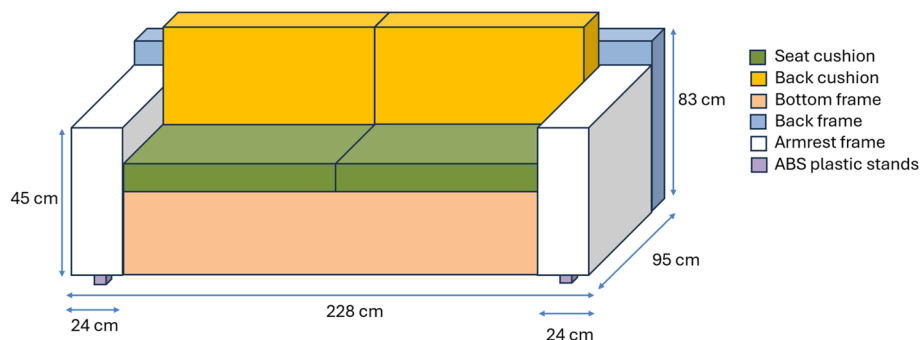


Fig. 2 Schematic illustration of the composition and dimensions of the three-seater sofa.

The density of ABS plastic is approximately 1.07 g cm^{-3} . The PU foam volume input is 0.44 m^3 with a density of 40 kg m^{-3} . The melamine FR content in the foam is estimated at 10% by weight.^{39–41} An average of 0.420 kWh electricity is used during sofa manufacturing processes.⁴² The production losses are assumed to be, on average, 7% of the total weight of the sofa, instead of the generally used range of 10–15%, reflecting the high efficiency of IKEA's production process.⁴³

The emissions of the FR to environmental compartments are estimated based on literature data.⁴⁴ During the production of the melamine FR, it is estimated that 0.025 wt% of the melamine produced is emitted to the industrial indoor air compartment, and 0.075% is emitted to the freshwater compartment. During the production of PU leather containing melamine FR, emissions occur in the manufacturing phase. It is similarly estimated that 0.025 wt% of the melamine FR used in the PU leather is emitted to industrial indoor air, and 0.075% is

emitted to freshwater. The same calculation is applied to the production of PU foam and production of the sofa (including handling, assembly, cutting, and surface treatment), *i.e.*, that 0.025% of the total FR content in the sofa is emitted to industrial indoor air, and 0.075% is emitted to freshwater.

For the use phase, the design life is estimated based on existing information within the furniture industry literature, ranging from 10 to 15 years depending on the use and materials of the sofa.^{42,45} A typical value of 10 years is applied⁴⁶ and variations are tested in the sensitivity analysis. In the use phase, no material or energy inputs are assumed, as cleaning is excluded from the analysis. However, emissions of the melamine FR during use are considered and provided in Table 2. The emissions of the FR during the use phase of the sofa are estimated to be 0.05 wt% of the FR content in the sofa to the air compartment, and 0.05% to the water compartment.⁴⁴ Naturally, there are no such emissions for the sofa without FRs.



Table 1 Unit process data for the manufacturing of the sofa with and without FR. FU = functional unit, PU = polyurethane, FR = flame retardant

Flow	Unit per FU	Sofa with FR	Sofa without FR
Input			
Polyurethane (PU) leather without FR	kg	3.40	4.86
Melamine FR in leather	kg	1.46	—
Electricity for PU leather production	kWh	7.3	7.3
Heat for PU leather production	MJ	10.7	10.7
PU foam without FR	kg	16.82	18.69
Melamine FR in PU foam	kg	1.87	—
Wooden frames	kg	50.64	50.64
ABS	kg	0.270	0.270
Metal screw	kg	0.375	0.375
Metal springs	kg	6.313	6.313
Electricity for sofa production	kWh	0.420	0.420
Output			
Sofa	kg	75.83	75.83
Production losses	kg	5.31	5.31
Melamine FR emissions from FR production (to air)	g	0.831	—
Melamine FR emissions from FR production (to water)	g	2.494	—
Melamine FR emissions from PU leather production (to air)	g	0.364	—
Melamine FR emissions from PU leather production (to water)	g	1.093	—
Melamine FR emissions from PU foam production (to air)	g	0.467	—
Melamine FR emissions from PU foam production (to water)	g	1.402	—
Melamine FR emissions from sofa production (to air)	g	0.831	—
Melamine FR emissions from sofa production (to water)	g	2.494	—

Table 2 Unit process data for use phase of the sofa with and without FR. FU = functional unit, FR = flame retardant

Flow	Unit per FU	Sofa with FR	Sofa without FR
Output			
Melamine FR emissions from sofa use (to air)	g	1.663	—
Melamine FR emissions from sofa use (to water)	g	1.663	—

For the EoL, municipal wood waste incineration in Sweden with heat and energy recovery is assumed considering the high content of wood and other combustible materials. Complete incineration is assumed, with no emissions of melamine FR (Table 3). Landfill is unusual for municipal solid waste in Sweden, a characteristic it has in common with many other European countries. The sofa with FR could be considered hazardous waste considering its FR content, but in practice, the owner will probably not differentiate between sofas with and without FR, making municipal incineration the most likely EoL. The energy recovery from incineration is estimated at 1.45 MJ

kg⁻¹ of electricity and 13.51 MJ kg⁻¹ of thermal energy, based on data from Swedish municipal waste incineration from Ecoinvent. All datasets used along with additional information and sources, are provided in the SI.

Life cycle impact assessment

The LCIA includes both midpoint and endpoint impact categories. First, all midpoint impact categories except toxicity are calculated using ReCiPe 2016 v1.03 (H), and then the midpoint toxicity impact categories for ecotoxicity (freshwater) and human toxicity (cancer and non-cancer) are calculated using

Table 3 Unit process data for the EoL phase of a sofa with and without FR. FU = functional unit, FR = flame retardant

Flow	Unit per FU	Sofa with FR	Sofa without FR
Input			
Waste management of sofa (incineration)	kg	75.83	75.83
Output			
Incineration heat generated	MJ	1024	1024
Incineration electricity generated	kWh	31	31
Melamine FR emissions from incineration (to air)	g	0	—



USEtox 2.12. USEtox is preferred for toxicity because of the possibility to calculate new CFs and since it is recommended by the Life Cycle Initiative.⁴⁷ Next, the endpoint impact category of human health is calculated using USEtox for human toxicity (cancer and non-cancer) and ReCiPe 2016 v1.1 for all other health-related impact categories (climate change, stratospheric ozone depletion, ionizing radiation, particulate matter formation, photochemical ozone formation, and water consumption). Both USEtox and ReCiPe calculate health impacts in terms of DALYs. All three value perspectives in ReCiPe are considered: Individualist (ReCiPe 2016 v1.1 (I)), Hierarchist (ReCiPe 2016 v1.1 (H)), and Egalitarian (ReCiPe 2016 v1.1 (E)).

In both ReCiPe and USEtox, the human health area of protection is expressed as the loss of healthy life years, *i.e.*, DALY, which accounts for both years of life lost, and years lived with disability due to disease. In USEtox, the endpoint modelling involves applying damage factors to translate the number of disease cases estimated at the midpoint level for cancer and non-cancer effects into DALYs at the endpoint level. Based on Huijbregts, Rombouts,⁴⁸ a conversion factor of 11.5 DALYs per case for cancer effects, and 2.7 DALYs per case for non-cancer effects is applied in USEtox.

The ecotoxicity CFs for melamine are calculated from the fate factor (FF) and exposure factor (XF) calculated in this study, while the effect factor (EF) for ecotoxicity is obtained from Aggarwal, Holmquist.⁴⁹ In contrast, the effect factors for human toxicity are calculated in this study. Eqn (1) is used to calculate the CFs.⁵⁰ In this equation, FF represents the steady-state distribution of the chemical across different environmental compartments after release. The XF represents the fraction of the chemical available to the exposed population. The EF represents the toxicity potential of the chemical.

$$CF = FF \times XF \times EF \quad (1)$$

While most toxicity CFs are already available in the USEtox database, it lacks a CF for non-carcinogenic effects of melamine. Therefore, new carcinogenic and non-carcinogenic human toxicity CFs for melamine are calculated using the USEtox 2.14 methodology.^{47,51} These CFs are necessary to convert melamine emissions into human toxicity impacts. To assess their reliability, the new CFs are compared with the existing CFs in the USEtox database. Experimental toxicity data is collected from the CompTox database and then compiled and harmonized to calculate both carcinogenic and non-carcinogenic human toxicity CFs.⁵² For non-carcinogenic effects, nine harmonized toxicity data points are used for inhalation, resulting in an $ED_{50,inh,noncanc}$ of 0.86 kg per lifetime, and 116 data points are used for ingestion, yielding an $ED_{50,ing,noncanc}$ of 0.55 kg per lifetime. For carcinogenic effects, eight harmonized data points for ingestion generated an $ED_{50,ing,canc}$ of 111 kg per lifetime. Since no inhalation data is available for carcinogenic impacts, a route-to-route extrapolation is performed from oral to inhalation exposure, resulting in an estimated $ED_{50,inh,canc}$ of 111 kg per lifetime. These ED_{50} values are then used to calculate the midpoint human health CFs (in cases per kg emitted) and the endpoint CFs (in DALY per kg emitted)

for both cancer and non-cancer effects of melamine emissions to various environmental compartments. All input data to the USEtox model are provided in the SI.

In a recent quantitative risk assessment, the benefit of FRs in sofas were estimated at 1.2 avoided fatalities per million protected persons per year, compared to sofas without FRs.⁵³ Since the average lifespan in Sweden in 2025 is 83.62 years,⁵⁴ the average DALY avoided fatality is 41.81 years. The Swedish average household size is 2 people⁵⁵ and we initially assume one sofa per household prior to the sensitivity analysis. From this, the marginal DALYs associated with fire risks are 0.001 DALY per FU (1.2 fatalities/million persons/year \times 2 persons/sofa \times 41.81 DALY/fatality \times 10 years).

Interpretation

The interpretation includes a scenario-based sensitivity analysis covering six aspects. First, this study considered an average of 30% of the FR in the PU leather based on the best available data in the literature.^{36,37} However, this concentration may vary. In the sensitivity analysis, the level of the FR in the PU leather is varied from 15% to 45% to analyze changes in impacts. Second, the EoL scenario for the sofa is changed from incineration to landfill. The primary impact of changing the EoL treatment is related to the emissions of the melamine FR. Under the incineration scenario, it is assumed that all the FR is fully combusted, resulting in no FR emissions contributing to human toxicity. In contrast, when the sofa is landfilled, emissions of the FR are assumed to be released to soil, leading to potential human toxicity and ecotoxicity impacts. Third, the cutoff approach is applied as baseline, in which the heat and electricity recovered from the incineration are provided burden-free to subsequent product systems, without crediting the sofa.⁵⁶ However, in the third scenario, the avoided burden by substitution approach is applied, where the heat and electricity from incineration are treated as substitutes to Swedish average heat and electricity, and the corresponding avoided impacts are credited for. Fourth, the design life of the sofa is assumed to be 10 years in the baseline scenario. In the sensitivity analysis, it is varied between 5 and 15 years, which affects the reference flow per FU. For a 5 year design life, the reference flow is 2 sofas, while for a 15 year design life, it is 0.67 sofas. Fifth, the number of sofas per householder can vary, *e.g.*, from 0.5 (*e.g.*, two people sharing one sofa) to 2 (*e.g.*, one person living alone in a large house with two sofas). The latter is not unreasonable given that the modal Swedish household is an individual and according to some statistics a majority of Swedes live alone.⁵⁷ This variation changes the reference flow per FU from 0.5 sofas to 2 sofas in the sensitivity analysis. Sixth, this study considered an average 10% of the FR in the PU foam based on the best available data in the literature.^{39–41} In the sensitivity analysis, the level of the FR in the PU foam is varied from 5% to 15% to analyze changes in impacts.

Results and discussion

This section first presents new CFs for melamine, followed by the LCIA results with and without melamine FR. Comparative results are provided in Fig. 4, highlighting potential



environmental impacts across different impact categories. Additionally, SI provides a detailed breakdown of the results across the life cycle stages.

Melamine human toxicity characterization factors result

All calculated midpoint and endpoint human health CFs for different compartments are provided in the SI, while the CFs used specifically in this study (for melamine emissions to household indoor air, industrial indoor air, continental freshwater, and continental natural soil) are provided in Table 4. The CFs in the current USEtox database are generally calculated from data collected over a decade ago. In contrast, this study compiled updated toxicity data for melamine, covering both cancer and non-cancer endpoints, as detailed in life cycle impact assessment section, leading to updated CFs.

In the USEtox database, the EF for carcinogenic inhalation exposure (based on $ED_{50,inh,cancer}$) is 321 kg per lifetime. In this study, the value calculated with updated data is 111 kg per lifetime. The lower ED_{50} value results from the inclusion of updated and more comprehensive toxicity data, with minimum values used in line with USEtox methodology. This reflects a potentially more accurate estimation of melamine's human health impacts. Fig. 3 presents a comparison of the CFs for melamine, covering both cancer and non-cancer effects across different compartments.

Midpoint-level results

Fig. 4 shows the midpoint-level results for the sofa with FR, expressed as a percentage of the impacts of the sofa without FR, based on ReCiPe 2016 v1.1 midpoint (H) impact categories and USEtox 2.12 ecotoxicity and human toxicity impact categories. The only difference in the modelling of the sofa with and without FR is the inclusion of the melamine FR, which accounts for approximately 4.4% of the total product weight. The production of melamine FR is a resource and energy intensive process, resulting in slightly increased impacts across several

categories, including climate change. Melamine emissions are included in the toxicity impact assessment, but only about 0.35 wt% of FR emitted in air and water compartment. As a result, the increase in non-cancer toxicity impacts of the sofa with FR is only about 2.3%, which is due to the relatively low emissions and the lower CFs of melamine compared to other contributors to toxicity in the product system. Among all impact categories, the only that shows a notable increase is freshwater consumption, due to water use in melamine production. In contrast, ionizing radiation and stratospheric ozone depletion impacts decrease slightly, as melamine replaces PU foam in the sofa, which has higher impacts in these categories. The absolute values for all impact categories are provided in the SI.

Fig. 4 also shows the hotspots of the 19 midpoint-level impact categories. The main contributing processes to the impact categories are the wooden frame, due to the large amount of wood used in the sofa, followed by the PU foam, and then the furniture's EoL. Other important contributors include metal springs, and PU leather. The melamine FR contributes relatively little to the overall impact, primarily due to the small quantity used and the relatively low per-kg impact of melamine.

Endpoint-level results

Fig. 5 shows the net health impact for the sofa with and without FR. Only the non-toxicity health impacts vary with the changes in value perspective, since that is inherent to ReCiPe 2016 and does not affect the USEtox results. This creates a limitation in comparing value perspectives, as the USEtox-based toxicity results remain constant across all three perspectives. The impacts from the impact categories in ReCiPe 2016 decrease considerably when moving from the egalitarian to the hierarchist and then individualist perspective. This trend shows that the choice of value perspective has a notable influence on the health impact.

When comparing the sofa with and without FR within the same value perspective, the main differences arise from the inclusion of FR emissions and fire-related fatalities. For the sofa with FR, the relative health impact from fire-related fatalities is

Table 4 Midpoint and endpoint cancer and non-cancer human health characterization factors (CFs) for melamine emitted to different compartments

Type of CFs	Emission compartment	CF		
		Cancer	Non-cancer	Total
Midpoint human health characterization factor [cases per kg emitted]	Emission to household indoor air	1.92×10^{-5}	2.47×10^{-3}	2.49×10^{-3}
	Emission to industrial indoor air	5.93×10^{-7}	7.85×10^{-5}	7.91×10^{-5}
	Emission to cont. freshwater	1.03×10^{-7}	2.05×10^{-5}	2.06×10^{-5}
	Emission to cont. natural soil	9.40×10^{-10}	1.88×10^{-7}	1.89×10^{-7}
Endpoint human health characterization factor [DALY per kg emitted]	Emission to household indoor air	2.21×10^{-4}	6.66×10^{-3}	6.88×10^{-3}
	Emission to industrial indoor air	6.82×10^{-6}	2.12×10^{-4}	2.19×10^{-4}
	Emission to cont. freshwater	1.18×10^{-6}	5.54×10^{-5}	5.66×10^{-5}
	Emission to cont. natural soil	1.08×10^{-8}	5.08×10^{-7}	5.19×10^{-7}



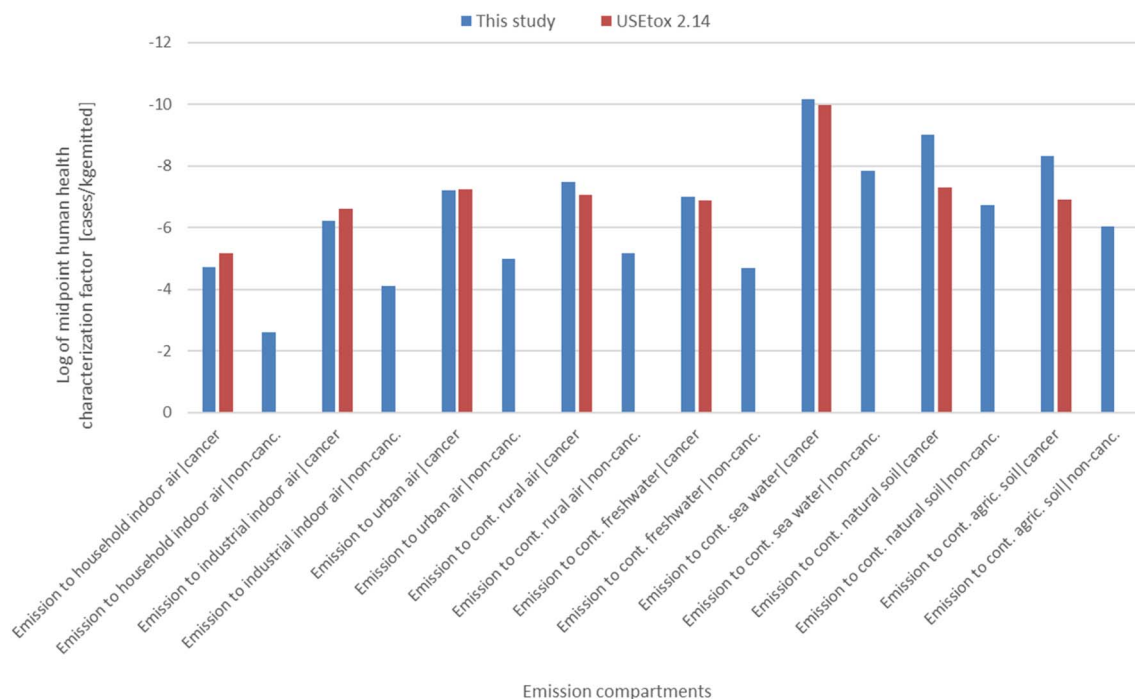


Fig. 3 Midpoint carcinogenic and non-carcinogenic human toxicity CF for melamine available in USEtox database vs. calculated in this study using the USEtox 2.14 methodology with updated data. Note that USEtox 2.14 does not provide ready-made carcinogenic CFs for melamine.

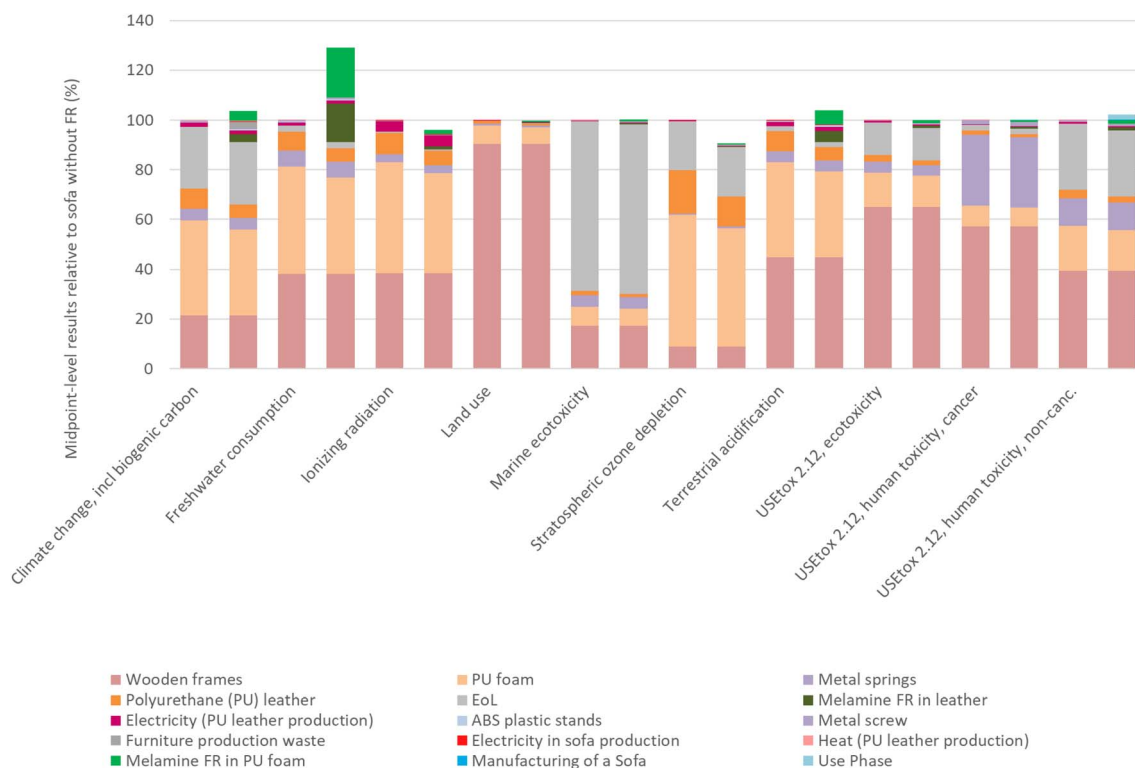


Fig. 4 Midpoint-level results for the sofa with melamine FR (right histograms per impact category) are presented as a percentage of the impacts of the sofa without FR (left histograms per impact category), based on ReCiPe 2016 v1.1 midpoint (H) impact categories and USEtox 2.12 ecotoxicity and human toxicity impact categories.



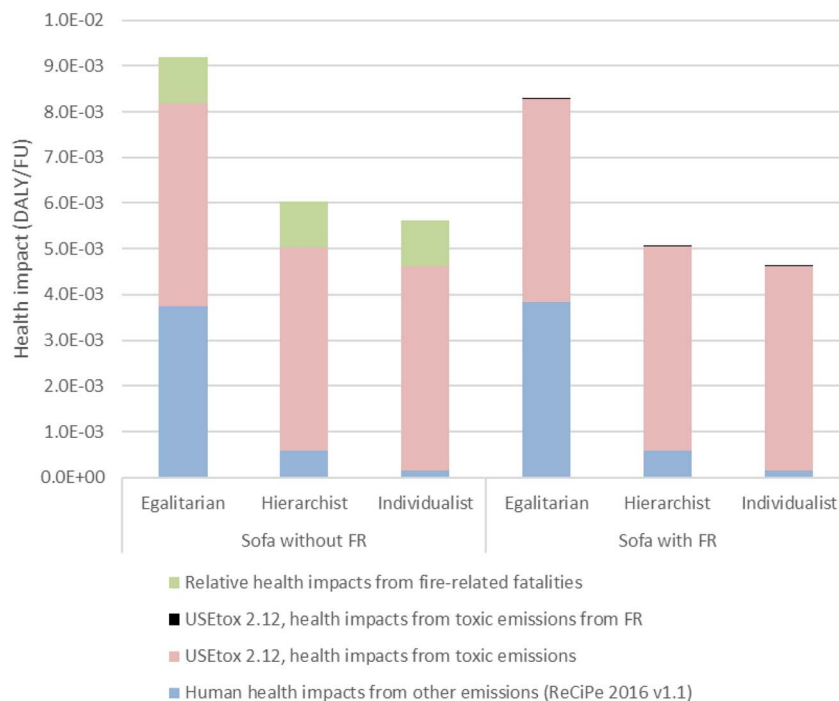


Fig. 5 Net health impact (DALY) of the sofa with and without FR, using the three value perspectives in ReCiPe 2016, Individualist (ReCiPe 2016 v1.1 (I)), Hierarchist (ReCiPe 2016 v1.1 (H)), and Egalitarian (ReCiPe 2016 v1.1 (E)). DALY = disability-adjusted life year, FU = functional unit, FR = flame retardant.

excluded, while the impact from FR emissions on human health is included. Conversely, for the sofa without FR, there are no emissions of FRs, but the relative health impact of fire-related

fatalities is included. Since the relative health impact from fire-related fatalities is higher than that from FR emissions, the net human health impact is greater for the sofa without FR.

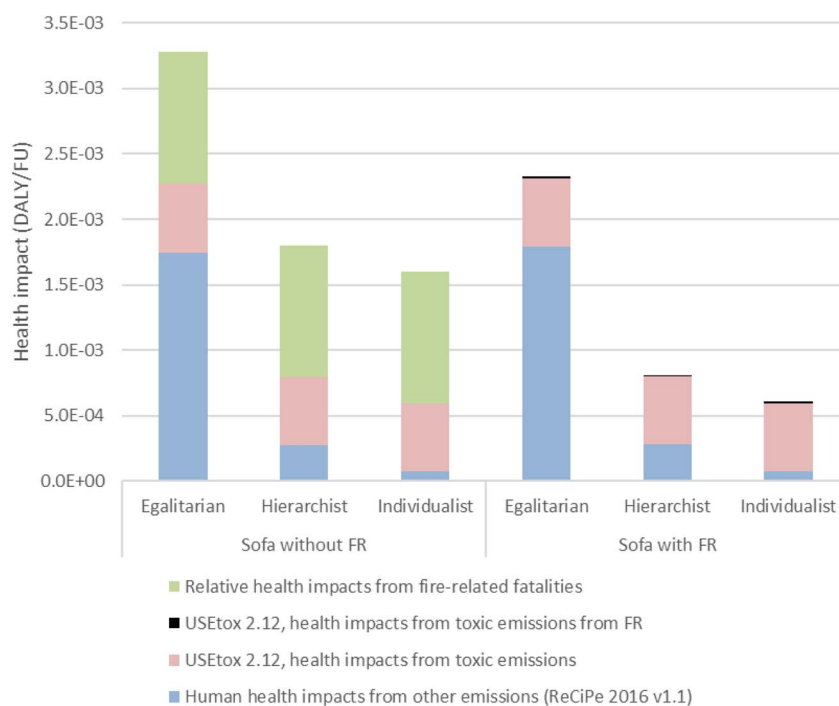


Fig. 6 Net health impact (DALY) of the sofa with and without FR when only the melamine-related materials including PU leather and PU foam are considered, using the three value perspectives in ReCiPe 2016, Individualist (ReCiPe 2016 v1.1 (I)), Hierarchist (ReCiPe 2016 v1.1 (H)), and Egalitarian (ReCiPe 2016 v1.1 (E)). DALY = disability-adjusted life year, FU = functional unit, FR = flame retardant, PU = polyurethane.



Fig. 6 shows the net health impact for the sofa with and without FR when only the melamine-related materials (PU leather and PU foam) are considered. The health impacts from other constituents (e.g., wood) are excluded to allow a clearer comparison of only the materials that differ between the two sofas. This approach reduces the health-related impacts from other emissions and USEtox 2.12 health impacts from toxic emissions. Overall, the reduction in health impacts is 72% for the individualist perspective, 84% for the hierarchist perspective, and 87% for the egalitarian perspective, compared to the case where all materials are included. Fig. 6 shows even more clearly that the sofa without FR obtains slightly higher health impacts due to the increased risk of fire, whereas the health impacts from melamine emissions for the sofa with FR are negligible.

Sensitivity analysis results

In this study, six sensitivity analysis are performed to assess the robustness of the results, as described in interpretation section. For each sensitivity analysis, results are calculated at both the midpoint and endpoint level. Only the midpoint results for the climate change impact category and the net health impacts are shown in the main article, but all results are provided in the SI.

Fig. 7 shows the net health impact and Fig. 8 the climate change impact for the sofas with and without FR, given the hierarchist value perspective. In the main scenario, the sofa without FR shows a higher net health impact compared to the sofa with FR, primarily due to the higher contribution from fire-related fatalities, which outweigh the human toxicity impacts of

melamine FR emissions. For climate change impacts, the sofa with FR shows approximately 2% higher impact than the sofa without FR. This increase is primarily due to the FR replacing other components of the PU leather that have lower impacts. Although the per-unit impact of the FR is high, its total share is only 4.4% of the sofa's total weight, resulting in a modest overall increase in climate impact.

In the first alternative scenario, the proportion of FR in PU leather is varied from the baseline of 30% to 15% and 45% of the total leather weight. This changes the total FR content in the sofa to 3.4% and 5.3% of its total weight. However, the health impact of the melamine FR emissions remains relatively small compared to other contributors, resulting in negligible changes in the net health impact. For climate change, the change in impact negligible (<0.4%).

In the second alternative scenario, the EoL process for the sofa is changed from incineration to landfill. Although the emission of the melamine FR increases under the landfill scenario, its contribution to the overall impact is negligible compared to the reduction in other emissions that occur when using landfill instead of incineration. While the human toxicity impact assessed *via* USEtox decreases slightly due to lower emissions of other substances, the ReCiPe-based health impacts increase under the landfill scenario. Overall, the net health impact shows a slight decrease; however, this change is <1% and can be considered negligible. For climate change, landfilling generally has a higher climate impact than incineration, resulting in a slight increase of about 3%.

In the third alternative scenario, the allocation approach is changed from cut-off to avoided burden by substitution. This

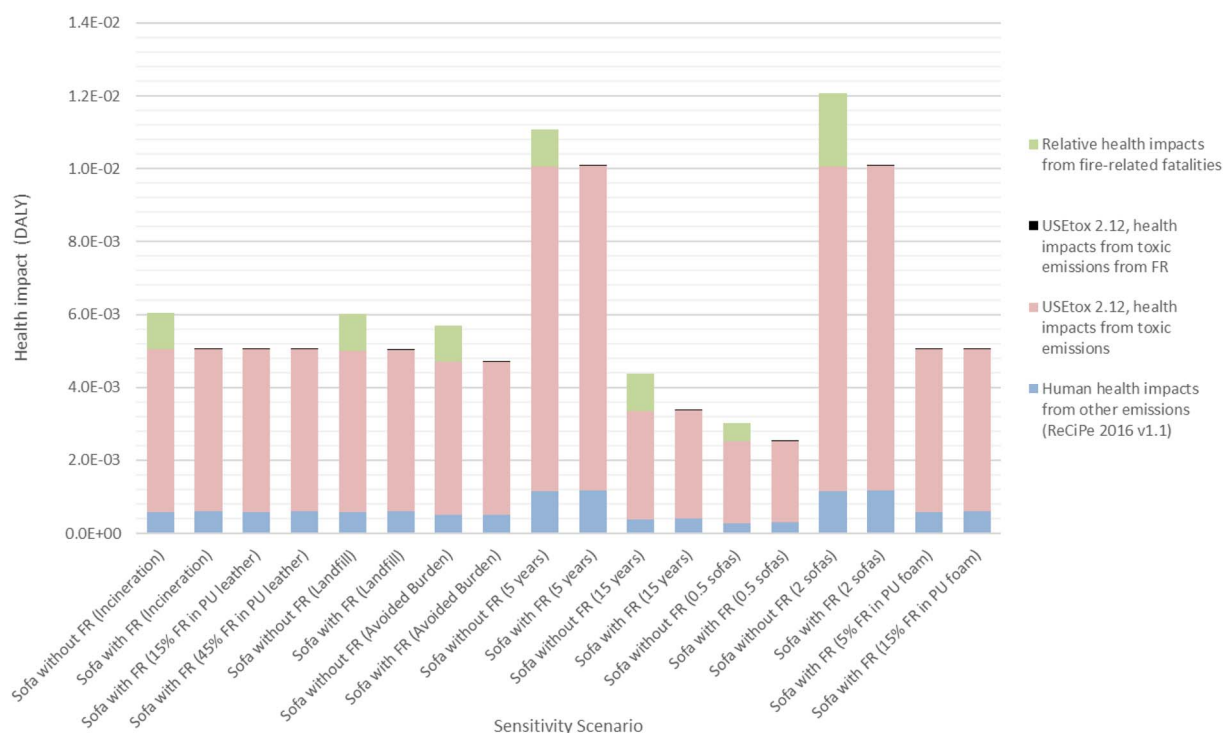


Fig. 7 Net health impact for the sofa with and without FR across five sensitivity analysis, using the hierarchist value perspective. FR = flame retardant, PU = polyurethane.



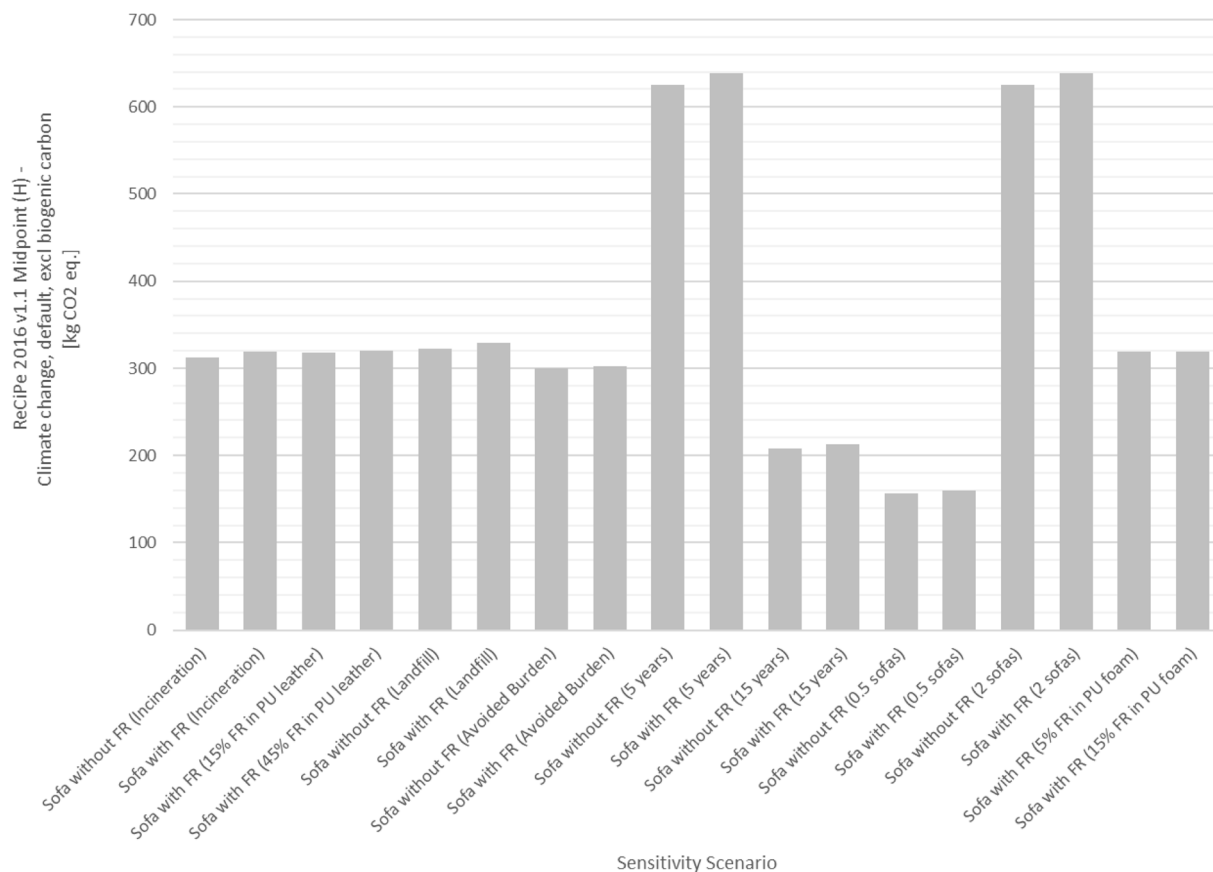


Fig. 8 Climate change impact for the sofa with and without FR across five sensitivity analysis, using the hierarchist value perspective. FR = flame retardant, PU = polyurethane.

results in a 6–7% decrease in the net health impacts compared to the baseline. The reduction is observed for both USEtox and ReCiPe, while the melamine FR impact remains unchanged. The primary reason for these reductions is the environmental credit assigned to heat and electricity generated from incineration, which are assumed to replace Swedish average heat and electricity, thereby reducing the overall impact. For climate change, this change yields a 4–5% reduction due to the credits.

In the fourth alternative scenario, the design life of the sofa varies from the baseline of 10 years to 5 years and 15 years. This change affects the reference flow: for a 5 year design life, two sofas are required to fulfill the functional unit (provision of a sofa over 10 years), whereas for a 15 years design life, only 0.67 sofas are needed. The impacts from ReCiPe, USEtox, and FR emissions scale with the reference flow: a shorter design life leads to increased impacts, while a longer design life results in decreased impacts. The climate impacts consequently double in the 5 year scenario and decrease by approximately 33% in the 15 year scenario. However, it is important to note that design life is not an arbitrary parameter that can be changed at will. In reality, extending or shortening the design life of a product would influence the material selection, manufacturing processes, durability, and maintenance requirements of the sofa. For instance, a longer design life would necessitate more durable (and potentially more resource-intensive) materials,

while a shorter design life could justify the use of less durable, lower-impact materials. Therefore, while this sensitivity analysis provides a hypothetical understanding of how design life affects environmental impacts, real-world implementation would require a more holistic consideration of material and functional aspects.

In the fifth alternative scenario, the number of sofas per householder varies from the baseline value of 1 to 0.5 and 2. This change also affects the reference flow of sofas per functional unit. If the number of sofas per householder is reduced to 0.5, the reference flow becomes 0.5 sofa per FU. Conversely, if increased to 2, the reference flow becomes 2 sofas per FU. As a result, the impacts calculated by ReCiPe and USEtox change proportionally. A reduction to 0.5 sofas per householder leads to a 50% decrease in impacts compared to the baseline case, while an increase to 2 sofas results in a 100% increase in impacts relative to the baseline. This linear relationship illustrates how household furniture use patterns can influence the environmental and health performance of the product system.

In the sixth alternative scenario, the proportion of FR in PU foam is varied from the baseline of 10% to 5% and 15% of the total foam weight. This changes the total FR content in the sofa to 3.2% and 5.6% of its total weight, which leads to a climate change impact variation of less than 0.1%, making the effect negligible. The health impact of the melamine FR emissions



also remains relatively small compared to other contributors, resulting in negligible changes in the net health impact.

Limitations and outlook

There are several limitations in this study that should be considered when interpreting the results. First, some processes are excluded from the LCA. These include transport of the sofa from the supplier to the user, packaging, internal transportation of components, and transport related to the sofa's EoL. Also excluded are inputs required for fire extinguishing, and the subsequent replacement of damaged items. Residential fires starting with non-flame-retarded polyurethane foam in upholstered furniture can potentially lead to the loss of an entire home if not contained, along with the release of associated hazardous emissions.^{17,22,58} This study includes only the loss of life and injuries from fires relative to the presence of FRs, not broader fire-related impacts. Only the health impact from the risk of fatalities is considered, which serves as a proxy for the net health burden related to fire incidents. However, expanding the scope to include such impacts would likely only strengthen our conclusion that the negative impacts of FR use are outweighed by the benefits.

Second, the estimated risk of fire-related fatalities from sofas without FRs is assumed to be 1.2 persons per million per year based on Runefors.⁵³ While this value is not specific to melamine-based FRs, it has been applied due to the lack of specific data and the general assumption that melamine is an effective FR.

The approach developed in this study can also be applied to other FRs and could be applied as a tool in the context of the "essential use" concept.⁵⁹ This concept shifts the question from whether a chemical is safe to whether it is essential for the function of the product.⁶⁰ Essential use often includes chemicals that contribute to health and safety, which is considered to justify their use.⁶¹ The method presented in this study enables the assessment of the net health impacts of FRs across a product's life cycle. By evaluating whether the inclusion of a FR leads to a net increase or decrease in health impacts, this approach supports informed decisions regarding the essentiality of FRs. In this study, the inclusion of melamine-based FRs resulted in a reduction in net health impacts, thereby supporting its essentiality from a health and safety standpoint.

Conclusions

This study illustrates an approach for comparing products with and without FR by evaluating their net health impacts alongside other LCA impact categories. A sofa with the FR melamine is used as an illustrative case. In conventional LCA studies, health impacts are often overlooked or underestimated due to data gaps, particularly the lack of CFs for many FR chemicals in the human toxicity category. This study addresses that gap by developing new CFs for melamine to improve the coverage of human toxicity assessments.

Beyond toxicity, the study demonstrates a methodological approach for calculating net health impacts of FR-containing

products and comparing them to FR-free products by considering several contributors to health along the life cycle: (i) relative health impacts from fire-related fatalities when FRs are not used, (ii) health impacts from toxic emissions (both cancer and non-cancer effects), and (iii) health impacts from other emissions such as those contributing to climate change. All these contributors are translated into health impacts using endpoint modeling (in DALYs).

In this case study, the product evaluated is a sofa containing melamine. Melamine is toxic but not extremely so, and constitutes a relatively small component of the sofa, which results in a minimal change in net health impacts when comparing the sofa without FR. However, this approach becomes increasingly important when applied to other products involving hazardous FRs with higher concentrations and toxicities, for which the health impacts could be considerable.

Author contributions

Rahul Aggarwal: conceptualization, data curation, formal analysis, investigation, methodology, software, visualization, writing – original draft. Rickard Arvidsson: conceptualization, data curation, methodology, supervision, validation, visualization, writing – original draft. Gregory Peters: conceptualization, data curation, funding acquisition, methodology, project administration, resources, software, supervision, validation, visualization, writing – original draft.

Conflicts of interest

There are no conflicts to declare.

Data availability

All data generated during this study are included in this published article and its supplementary information (SI). Supplementary information is available. See DOI: <https://doi.org/10.1039/d6su00022c>.

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