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A comparative approach to evaluate the toxicity of building materials through life cycle assessment

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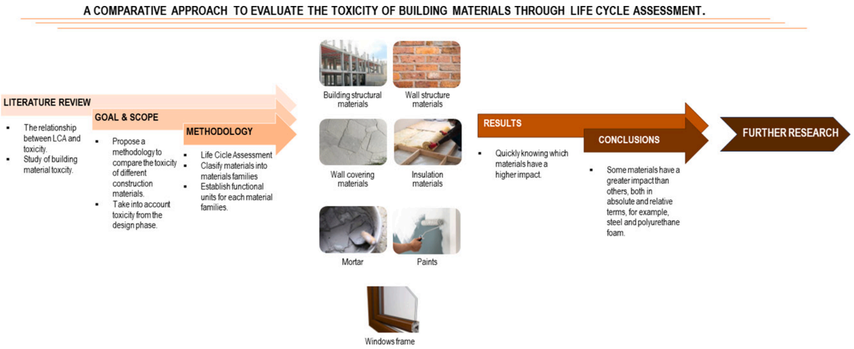
HIGHLIGHTS

- Toxicity of construction materials often ignored in favour of GWP impact.
- To enhance material selection including toxicity, apply comprehensive life cycle assessment.
- Some material families widely used, as insulation or paints, have high human and eco-toxicity impact.
- To improve databases, we must include more building materials as well as all the life cycle phases.
- Comparisons of materials based on toxicity are crucial for ranking materials.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: This paper addresses the lack of research that compares the toxicity of commonly used construction materials. The toxicity of construction materials has received less attention, despite its importance within the Life Cycle Assessment methodology. All aspects, including toxicity, need to be analysed throughout the life cycle of the material to understand its true behaviour.
Aim: The purpose of this study is to propose a methodology to compare the toxicity of different construction materials and highlight the need to consider toxicity criteria in the selection of materials during the design phase. The study seeks to fill the gap in the existing literature by providing information on the comparative toxicity of the most common building materials.
Methodology: The study follows Life Cycle Assessment methodology as established by the ISO 14040:2006 and ISO 14044:2006 standards. For this study, statistics were consulted to identify the most used materials in the construction sector; then, from this group of materials, those available in the Ecoinvent 3.7.1 database were selected. For comparison, these materials were categorised into material families and a functional unit was

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Abbreviations: ATP, aquatic ecotoxicity; COVs, Volatile Organic Compounds (COVs); CTU, comparative toxic units; CTUh, comparative toxic unit for human toxicity; CTUe, comparative toxic unit for ecotoxicity; GWP, global warming potential; HTP, human toxicity; JRC, Joint Research Center; LCA, Life Cycle Assessment; LCIA, Life Cycle Impact Assessment; TTP, terrestrial ecotoxicity.

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established to compare them. Finally, all materials were compared with each other, using 1 kg as the functional unit.

Results: When we conduct a comparative analysis of various materials and categorise them into groups, it becomes readily apparent which materials demonstrate a less favourable performance with respect to their toxic properties. This approach allows us to discern and pinpoint those materials that present a more concerning level of toxicity relative to others, facilitating informed decision-making in terms of construction material selection and design.

Conclusions: By comparing all materials with each other using 1 kg as the functional unit, we can conclude that some materials have a greater impact than others, both in absolute and relative terms, for example, steel and polyurethane foam.

1. Introduction

The construction sector plays a fundamental role in the global economy, but its environmental impact, particularly carbon dioxide (CO2) emissions, has raised increasing concerns in recent decades. This increase in CO2 emissions has led environmental assessments to focus on this aspect, leaving other equally important impacts, such as the toxicity of construction materials, in the background. In this context, this article aims to address the pressing need to assess not only the contribution to global warming, but also the toxicity of construction materials from a comprehensive perspective, incorporating life cycle assessment as the primary tool. The toxicity of materials used in construction not only affects the environment, but also has a significant impact on human health (Collinge et al., 2013; Buildings and their Impact on the Environment: A Statistical Summary, 2023), highlighting the importance of considering this factor as a fundamental element in architectural design.

Through the formulation of a robust and systematic methodology, this article seeks to provide a solid foundation for the comparison of construction materials (Statista Research Department, n.d.) from the perspective of their toxicity, thus contributing to the reduction of CO2 emissions and the design of healthier living spaces for society.

2. State of the art

This paper arises because of the needs identified in previous research regarding the toxicity of construction materials (Rey-Álvarez et al., 2022). In that review, the toxicity of construction materials was approached from two different perspectives: on the one hand, the toxicity formulation within the Life Cycle Assessment (LCA) methodology and, on the other hand, the study of the toxicity of construction materials itself. For this analysis, more than 150 articles were examined, from which several conclusions were drawn, such as the need to standardise Life Cycle Assessment (LCA) databases to avoid distortions, the need to incorporate more substances widely used in the construction sector, or the requirement to improve LCA calibration to prevent underestimating toxic emissions.

Among the conclusions obtained in the review, it was detected that interest in recent years has focused mainly on zero-energy buildings, leaving the rest of the ecological aspects of construction in the background (Hu, 2019). In this sense, the part of the design that includes human health aspects has been relegated to a secondary role. This can also be seen in the applicable regulations regarding material evaluation, where human toxicity is not a mandatory aspect, unlike the contribution to climate change or acidification (ISO 14044:2006(es), 2023; ISO 14040:2006(es), 2023). This perspective is fundamental within the Life Cycle Assessment, since, to know the true behaviour of a material or process, all aspects, including toxicity, must be analysed in all phases of the life cycle.

Although comparisons are common for CO_2 emissions (Balasbaneh and Sher, 2021; Dabaieh et al., 2020) and embodied energy (Dixit and Singh, 2018; Galán-Marín et al., 2015; Gaspar and Santos, 2015; Jia Wen et al., 2015; Luo et al., 2016; Nicolae and George-Vlad, 2015; Praseeda et al., 2015; Zeitz et al., 2019), this is not the case for toxicity, which is equally important as the other categories. These comparisons, made within the framework of the data provided by the Life Cycle Assessment for each material, allow prioritising and ranking the chosen materials based on empirical data.

As it can be seen in Table 1, the lack of articles that compare the toxicity of different materials means that it is necessary to refer to specific articles about each material. This poses the problem of the criteria

Table 1
Classification of articles in material comparison. Table made by the authors.

Reference	Material	Comparative	LCA Stage			Toxicity	
			Production	Use	Demolition	Data input	Data studied
(Chen et al., 2022)	Structural materials	Embodied energy and carbon emissions	X				
(Andersen et al., 2022)	CLT; concrete	Environmental impacts	X	X	X	X	
(Llantoy et al., 2020a)	Insulation materials	Environmental impacts	X	X		X	
(Ryberg et al., 2021)	Structural materials; wall covering; insulation	Environmental impacts	X	X	X	X	X
(Kumar et al., 2020)	Insulation materials	Properties and performances		X			
(Garcia-Ceballos et al., 2018)	Constructive solutions	Environmental impacts	X	X	X		
(Hadj Sadok et al., 2022)	Cementius materials	Environmental impacts	X			X	X
(Kobetičová and Černý, 2019)	Building materials	Terrestrial eutrophication	X				
(Füchsl et al., 2022a)	Insulation material	Environmental impacts	X			X	X
(Botejara-Antúnez et al., 2022)	Flat roof systems	Environmental impacts	X	X	X	X	X
(Duan et al., 2022)	Structural materials	Environmental impacts	X	X	X		
(Hahnel et al., 2021)	Flooring systems	Environmental impacts	X	X	X		
(Cruz Rios et al., 2019)	Wall framing systems	Environmental impacts	X	X	X		
(Kamali et al., 2019)	Structural materials	Environmental impacts	X	X	X		
(Adelfio et al., 2022)	Innovative materials	GWP	X				

Table 2
Toxicity results for 1m^3 of building structural materials.

	Building material	Density	Thermal conductivity	Human toxicity		Ecotoxicity
	m3	(Kg/m3)	(W/mK)	(CTUh)		(CTUe)
				non-cancer	cancer	
CO	Concrete, 30–32 Mpa	2327	1,65	2,45E-06	9,71E-08	3645,95
RCO	Reinforce concrete	2677	1,65	1,52E-05	5,11E-06	17,746,65
CLT	Cross-laminated timber	490	0,13	4,53E-06	4,12E-07	6507,08
ST	Structural timber	500	0,12	2,32E-06	1,36E-07	4132,60
STL	Steel	7850	50,2	3,33E-04	1,31E-04	368,968,31

used in these studies, where the same database is not always used, or the same criteria are not used. All of this makes it very difficult to choose a material based on toxicity criteria, both for technicians and consumers.

If we delve further into the articles analysed in Table 1, it becomes evident that not all examine all the life cycle phases of materials; only articles (Zeitz et al., 2019; Andersen et al., 2022; Ryberg et al., 2021; Kobetičová and Černý, 2019; Füchsl et al., 2022a; Botejara-Antúnez et al., 2022; Duan et al., 2022; Hahnel et al., 2021) do so. Among the articles that do not investigate all phases, only 2 address toxicity (Kumar et al., 2020; Hadj Sadok et al., 2022), and of the articles covering all phases, 2 also analyse toxicity (Andersen et al., 2022; Kobetičová and Černý, 2019). Among the remaining articles, some include toxicity data, but do not conduct an analysis (Zeitz et al., 2019; Chen et al., 2022). This leaves us with a very low percentage of articles that provide a comprehensive perspective on the life cycle of materials and encompass all impact categories.

As mentioned above, because of the scarcity of articles providing information on the behaviour of materials with regard to toxicity, making design decisions while considering these aspects becomes challenging. Therefore, we believe that it is necessary to establish a comparison of the most commonly used construction materials (Statista Research Department, n.d.), with toxicity as the primary category of analysis.

3. Materials and methods

The first part of this study was carried out following the life cycle assessment methodology established by the ISO 14040:2006 (ISO 14040:2006(es), 2023) and ISO 14044:2006 (ISO 14044:2006(es), 2023) standards. In addition to classifying materials according to their function, they will be compared on a functional level by establishing functional units that allow it. For this first part of the study, statistics were consulted to identify the most used materials in the construction sector; then, from this group of materials, those available in the Ecoinvent 3.7.1 database were selected. Once the materials that can be analyse have been identified, they have been divided into material families based on their function within the building.

These materials are divided into these families: structural materials, wall materials, coating materials, mortars, insulation materials, paints, and types of window frames. Different functional units have been selected for each of them: for structural materials, we have chosen 1 m3, for wall materials 1 m2, for coatings 1 m2, for mortars 1 kg, for insulation 1 m2 with the same thermal resistance, for paints 1 kg, and for window frames 1 m2 with the same thermal resistance. These functional units have been chosen based on their function within the building, being the most representative for each family. Impact values are presented in both normalised and characterised forms.

In the second part of the study, a correlational analysis was conducted among three impacts: human cancer toxicity, human non-cancer toxicity, and ecotoxicity. The R^2 factor was used to determine if these variables were correlated with each other. The purpose of this second part is to facilitate the comparison of all materials, and thus, a functional unit of 1 kg was established. Due to the dispersion of the data, the materials were divided into three categories: the bottom third with the lowest impact values, the middle third with medium impact values, and the upper third with the highest impact values. The purpose of these figures is twofold: firstly, to discern patterns of behaviour within material families, and secondly, to investigate potential correlations between the human toxicity cancer and non-cancer and ecotoxicity.

The categories selected for analysis were those related to human toxicity (HTP) and ecotoxicity (ATP aquatic ecotoxicity, TTP terrestrial ecotoxicity). As stated in the European Regulation 15804 + A2, the impact of these categories will be calculated using the USEtox 2.0 method (until the modified USEtox model is available in the EC-JRC) (UNE-EN 15804:2012+A2:2020 Sostenibilidad en la construcción. D, 2023).

The Life Cycle Impact Assessment (LCIA) model USEtox, developed in 2008 (Rosenbaum et al., 2008) is the only one accepted by the European Commission. The LCIA is a fundamental part of any Life Cycle Assessment as it allows quantifying the magnitude and importance of potential environmental impacts. Therefore, USEtox was born as a model based on scientific consensus. In addition to being the only method that contains a specific parameter for geographic characterisation (Belyanovskaya et al., 2020) includes a protocol to extrapolate exposure routes, moving from oral intake data to inhalation (Rosenbaum et al., 2011). Unlike other impact categories in which the reference substance is used, in the USEtox methodology, the toxicity categories are expressed in terms of comparative toxic units (CTU, CTUh for human toxicity; CTUe for ecotoxicity) per kg of emission, therefore, these units are dimensionless. The category of human toxicity is divided into cancer / noncancer.

For human toxicity impacts, the impact category indicator is specified as CTUh per kg emitted (unit in SimaPro), which is related to disease cases per kg emitted (unit in USEtox). Concerning the impacts of aquatic ecotoxicity, the impact category indicator is denoted as CTUe per kg emitted (unit in SimaPro), which is calculated as: PAF × m^3 × day per kg emitted (unit in USEtox).

For this case study, a cradle-to-gate approach (A1-A3 production phase) approach has been chosen because the available toxicity data only pertain to the production phase. For each family of materials, a different functional unit is established based on its function. For example, for insulation, 1m^2 of insulation with the same thermal conductivity is chosen, for structures, 1m^3, and for mortars, 1 kg. For the stages analysed, European averages were selected from the Ecoinvent 3.7.1 database (Frischknecht and Rebitzer, 2005; Frischknecht et al., 2005). As these are average data, their application in each European country depends on the degree to which specific characteristics of each country, such as energy mix, manufacturing or extraction of raw materials, approximate these data. A static approach has been used for the study, so the values taken are intermediate values within the systems analysed, without including variation over time. The software used for the study is SimaPro 9.3.

4. Results and discusion

In Sections 4.1 to 4.7, the toxicity results of the different life cycle assessments can be seen according to the different classifications of the selected construction materials. The selected families are: structural

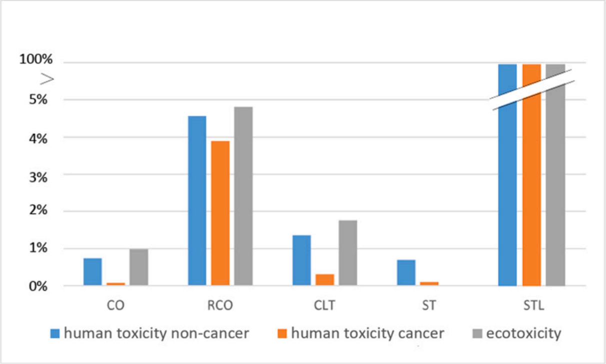


Fig. 1. Toxicity results for 1m^3 of building structural materials.

materials, materials used for walls, wallcovering, insulations, mortars, paints, and window frames. For each category, a functional unit has been selected to allow an effective comparison between materials. Furthermore, in Section 4.8, the results of comparing all materials with each other using 1 kg as the functional unit will be presented.

4.1. *Building structural materials.*

From the materials included in the chosen database, those that are most relevant for their use as part of the structure have been selected. These are: concrete (cement, gravel and water) (CO), reinforced concrete (cement, gravel, water and steel) (RCO), cross-laminated wood (CLT), structural timber (ST)l and steel (STL). The functional unit in which the data are reflected is m^3 (Table 2) (Fig. 1).

As the data in the graph show, the impacts of steel far exceed those of other materials. Even in the case of reinforced concrete, the results are influenced by the percentage of steel they contain. These high values are due, among other reasons, to the emissions of heavy metals such as cadmium or arsenic, as well as other compounds such as SO_2 and NO_x (Van Caneghem et al., 2010). Despite these values, steel recycling has been shown to contribute to reducing these impacts (Morris et al., 2021) although these data are not available in the database (Fig. 1).

In general, wood products tend to have a lower environmental impact, especially those that are less processed (Sathre and González-García, 2014). This can be verified by looking at the difference between the structural wood and the cross-laminated wood data.

If we compare the five materials, we can see that in relation to human toxicity there is not much difference between them, being in all cases quite low values. The main difference is found in the category of ecotoxicity.

This is mainly due to the use of petroleum-based adhesives that contribute to the emission of toxic gases (e.g., Volatile Organic Compounds (COVs) and formaldehyde) that are very harmful to the environment (Sotayo et al., 2020).

This aspect leaves room for improvement, specifically in the replacement of conventional resins such as urea-formaldehyde and melamine-formaldehyde with other natural resins with the same final specifications. Depending on the amount of resin replaced, the results on toxicity aspects would be improved, but also at equivalent levels of CO2 emissions (Wang et al., 2017).

4.2. *Wall structure materials*

From the materials available in the database, those most relevant in terms of the main structure of the walls have been chosen, in this case: ceramic brick (CYB), concrete block (CB) and drywall (GB). The reference functional unit is a 1m^2 wall with the same thermal conductivity (Table 3) (Fig. 2).

Table 3
Toxicity results for 1m^2 of wall structure materials.

	Building material	Density	Thermal conductivity	Thickness		Human toxicity		Ecotoxicity
	Kg	(Kg/m3)	(W/mK)	m	Kg/m2	(CTUh)		(CTUe)
						non-cancer	cancer	
CYB	Clay brick	1788	0,94	0,05	89,4	1,38E-07	2,91E-08	2,06E+02
CB	Concrete block	2150	1,75	0,093	199,95	3,24E-07	2,69E-08	4,81E+02
GP	Gypsum plasterboard	612	0,18	0,004	2448	8,38E-09	3,62E-10	3,05E+01

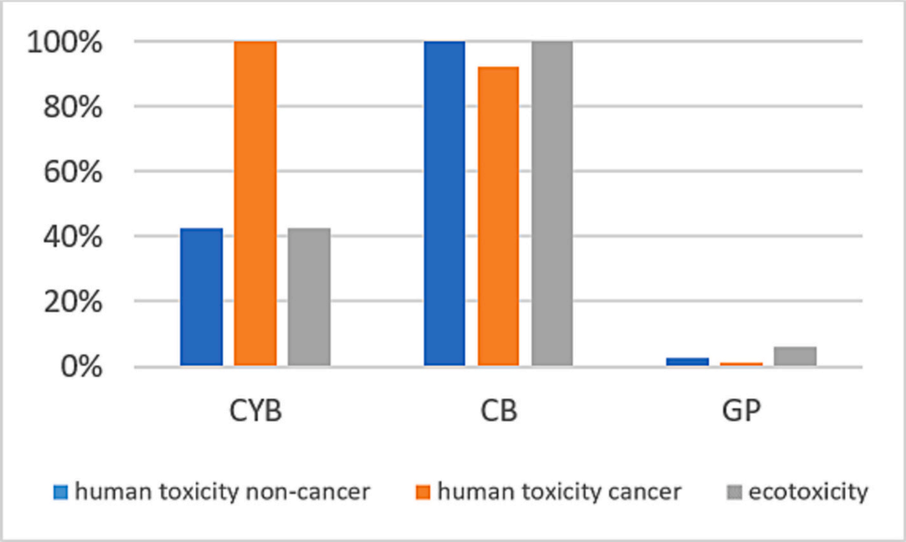


Fig. 2. Toxicity results for 1m^2 of wall structure materials.

Table 4
Toxicity results for 1m^2 of materials used for wall covering materials.

	Building material	Density	Thermal conductivity	Thickness		Human toxicity		Ecotoxicity
	Kg	(Kg/m3)	(W/mK)	m	kg/m2	(CTUh)		(CTUe)
						non-cancer	cancer	
CP	Cement plaster	2275	0,71	0,02	45,5	3,35E-08	1,28E-09	4,97E+01
NS	Natural stone plate	2750	1,7	0,03	82,5	3,17E-07	1,07E-08	6,48E+02
CT	Ceramic tile	2000	1,2	0,01	20	4,29E-07	1,54E-08	4,03E+02

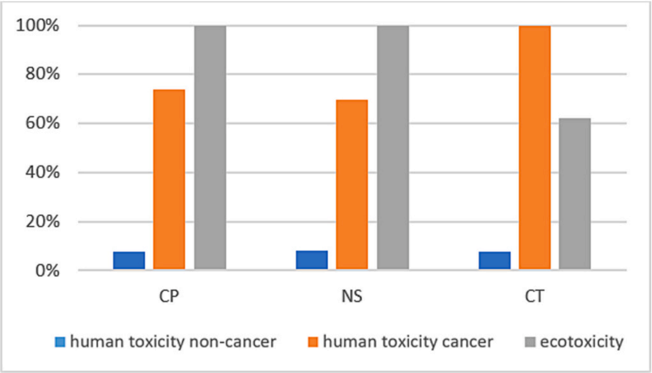


Fig. 3. Toxicity results for 1m^2 of materials used for wall covering materials.

As it can be seen, the results are very favourable for the case of drywall. This is due, among other things, to its lightness, which allows to use less material to cover the same surface (Valencia-Barba et al., 2021).

4.3. *Wall covering materials*

In the case of coatings, cement plaster (CP), natural stone cladding (NS) and ceramic tile (CT) were selected for study. The selected functional unit is 1m^2 (Table 4) (Fig. 3).

In this case, although the densities of the three materials are relatively similar, we can see that the impacts related to ceramic cladding are considerably higher than those related to the rest. This is mainly due to the concentration of heavy metals found in this type of material and that pose a high environmental risk (Andreola et al., 2019).

4.4. *Insulation materials*

To make the comparison between insulations, different materials included in the database have been chosen, whose use is widespread: 100 % recycled extruded polystyrene (P-100), extruded polystyrene 45 % recycled (P-45), rock wool (SW), extruded polystyrene for exterior insulation (PP), extruded polystyrene (P), cork (C) and polyurethane foam (PU). The selected functional unit is 1 m^2 of insulation with the same thermal conductivity (Table 5) (Fig. 4).

The first thing that is surprising about the result of these data is that cork has higher potential impacts than the rest of the insulation materials. In this case, it is because in the database used, the use of synthetic resins as a binder is considered, instead of the cork resin itself, which would result in better environmental performance (Tártaro et al., 2017).

The second thing we can see is that polyurethane foam has the highest results for human toxicity and ecotoxicity, being around 10 times higher than extruded polystyrene and rock wool. Despite its slightly better thermal performance compared to other insulation materials studied, given these results, and knowing that impacts in terms of GWP and water consumption are also significantly high, the continued use of polyurethane foam as insulation does not seem reasonable, and other more environmentally friendly alternatives should instead be chosen (Audenaert et al., 2012).

The comparison between the three types of extruded polystyrene foam is also worth noting. In this case, three types with different percentages of recycled material were chosen: 0 %, 45 %, and 100 %. When we look at extruded polystyrene foam with no recycled material, the environmental performance of rock wool is significantly better. This situation changes with the extruded polystyrene foam with 45 % recycled material and 100 % recycled material. In both cases, the impacts are reduced by more than half in the first case and by one sixth in the second.

Given these results, it would be logical to think that the market trend should be in line with offering more products with recycled material, as

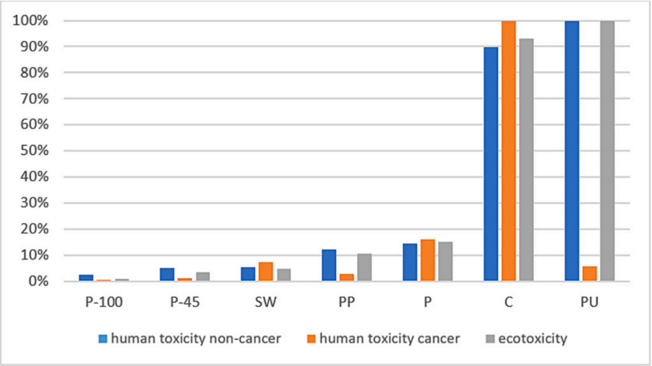


Fig. 4. Toxicity results for 1m^2 of insulation materials with the same thermal conductivity.

Table 5
Toxicity results for 1m^2 of insulation materials with the same thermal conductivity.

	Building material	Density	Thermal conductivity	Thickness		Human toxicity		Ecotoxicity
	Kg	(Kg/m3)	(W/mK)	m	Kg/m2	(CTUh)		(CTUe)
						non-cancer	cancer	
P-100	Polystrene foam slab 100 % recycled	28	0,036	0,07	1,96	7,30E-09	3,37E-10	65,295,784
P-45	Polystyrene foam slab 45 % recycled	28	0,036	0,07	1,96	1,36E-08	1,09E-09	26,607,345
SW	Stone wool	20	0,03	0,06	1,2	1,44E-08	6,12E-09	3,63E+01
PP	Polystyrene foam slab for perimeter insulation	33	0,033	0,06	1,98	3,35E-08	2,33E-09	7,65E+01
P	Polystyrene foam slab	30	0,036	0,07	2,1	3,92E-08	1,36E-08	1,10E+02
C	Cork Slab	180	0,037	0,072	12,96	2,42E-07	8,40E-08	6,77E+02
PU	Polyurethane, flexible foam	48	0,026	0,05	2,4	2,70E-07	4,95E-09	7,29E+02

Table 6
Toxicity results for 1 kg of mortars.

	Building material Kg	Density (Kg/m3)	Thermal conductivity (W/mK)	Human toxicity (CTUh) non-cancer	Human toxicity (CTUh) cancer	Ecotoxicity (CTUe)
C-21	Cement, alternative constituents 21–35 %	–	–	4,70E-09	1,25E-10	4,97E+00
CF-15	Cement, pozzolana fly ashes 15–50 %		–	4,51E-09	1,40E-10	7,60E+00
C-45	Cement, alternative constituents 45 %	–	–	5,00E-09	1,51E-10	7,72E+00
CF-6	Cement, portland fly ashes 6–20 %	2400	–	5,36E-09	1,56E-10	8,49E+00
CF	Cement, Portland	3150	0,53	6,10E-09	1,80E-10	9,63E+00
C-6	Cement, alternative constituents 6–20 %	–	–	5,81E-09	1,71E-10	1,01E+01
LM	Lime mortar	1350	0,73	5,31E-09	1,84E-10	1,02E+01
C	Cement plaster	2275	0,71	1,47E-06	5,60E-08	2,18E+03

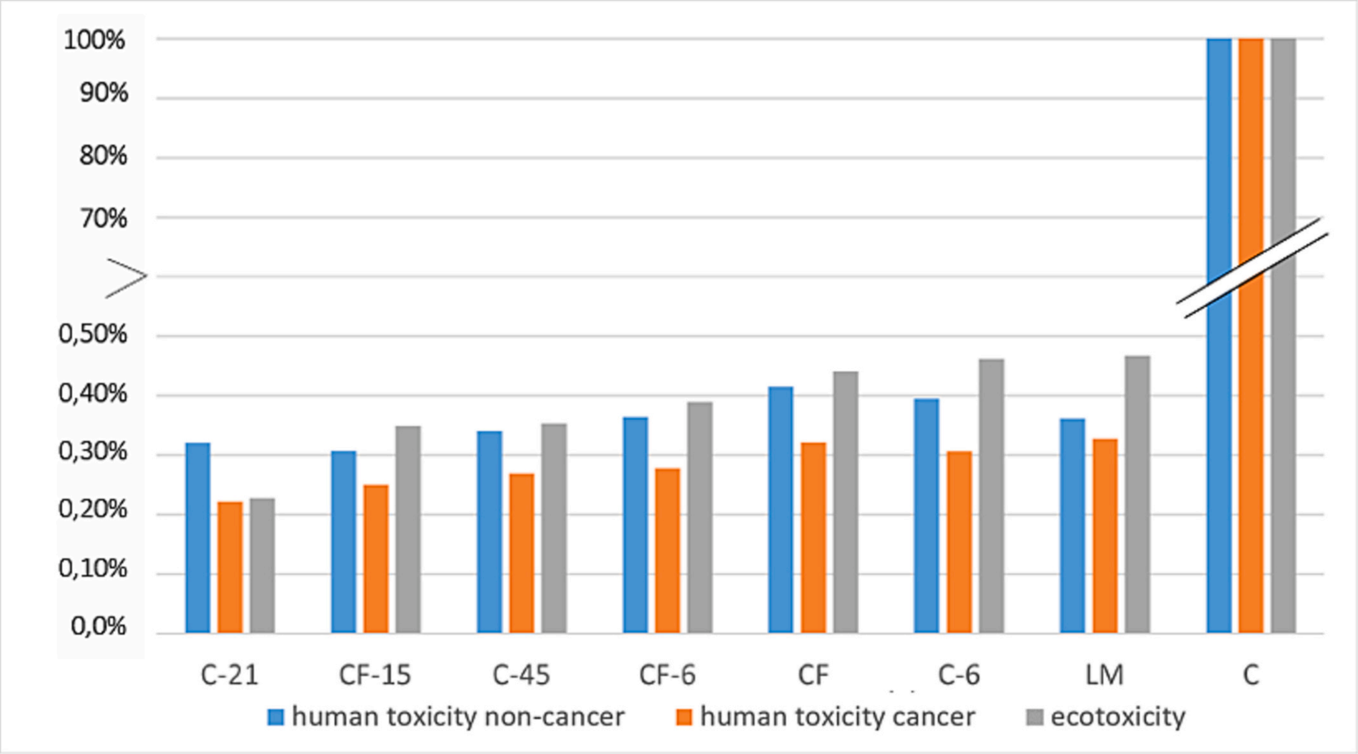


Fig. 5. Toxicity results for 1 kg of mortars.

is the case for extruded polystyrene, or insulation of natural origin, as is the case for cork. Likewise, materials such as polyurethane foam should gradually disappear from the market to make room for less pernicious alternatives (Pargana et al., 2014; Füchsl et al., 2022b; Llantoy et al., 2020b).

4.5. Mortars

For comparison between mortars, different compositions have been chosen to check the environmental performance: cement mortar with alternative components 21–35 % (C-21), cement mortar with alternative components 45 % (C-45), cement mortar with alternative components 6–20 % (C-6), portland cement (CF), portland cement with fly ash 6–20 % (CF-6), pozzolanic cement with fly ash 15–50 % (CF-15), lime mortar (LM) and cement mortar (C). The selected functional unit is 1 kg (Table 6) (Fig. 5).

In this case, unlike what we have seen in insulation, increasing the percentage of alternative material (recycled or not) does not equate to better environmental performance. In all three cases, as the percentage of alternative materials increases, the result of possible toxic impacts has

Table 7
Toxicity results for 1 kg of paints.

	Building material Kg	Density (Kg/m3)	Thermal conductivity (W/mK)	Human toxicity (CTUh) non-cancer	Human toxicity (CTUh) cancer	Ecotoxicity (CTUe)
PS	Alkyd paint solvent-based	–	–	1,85E-07	9,06E-09	1,75E+02
PW	Alkyd paint water-based	–	–	1,81E-07	8,90E-09	1,77E+02

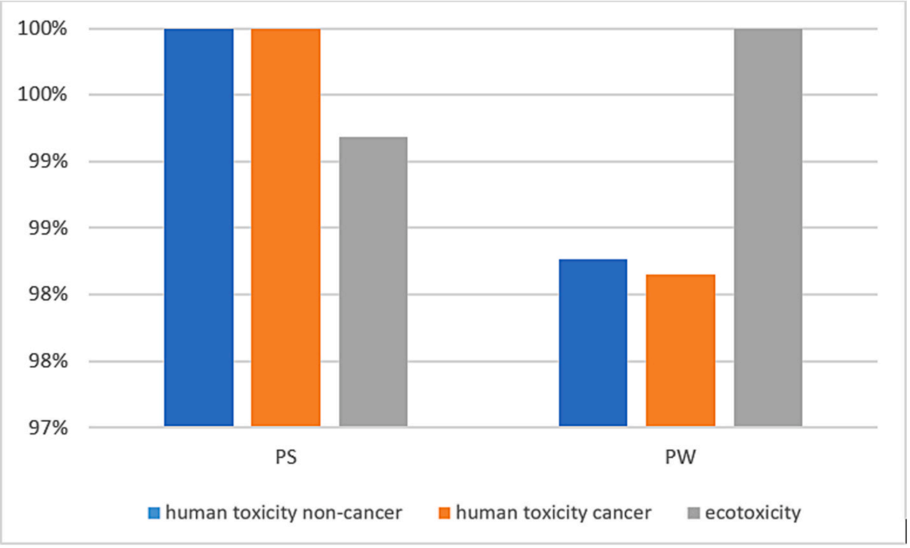


Fig. 6. Toxicity results for 1 kg of paints.

increased. This is often due to the use of materials for which there are no adequate protocols to measure their toxicity (Rodrigues et al., 2017).

Table 8
Toxicity results for 1 m2 of windows frames with the same transmittance.

	Building material	Thermal conductivity	Human toxicity		Ecotoxicity
	m2	U = (W/m2K)	(CTUh)		(CTUe)
			non-cancer	cancer	
WF	Wood frame	1,5	4,11E-06	3,09E-07	5,13E+03
PVCF	Polyvinyl chloride frame	1,6	5,58E-06	9,72E-07	7,34E+03
WMF	Wood-metal frame	1,6	7,43E-06	4,93E-07	9,90E+03
AF	Aluminium frame	1,6	1,46E-05	8,78E-07	1,69E+04

4.6. *Paints*

In this case for the comparison between paints, two have been taken, solvent-based paint (PS) and water-based paint (PW). The selected functional unit is 1 kg (Table 7) (Fig. 6).

Although paints are widely recognised to contribute significantly to the emissions of volatile organic compounds (VOCs) and microplastics during their use phase (Gaylarde et al., 2021), the data contained in the database pertain exclusively to the production phase. This data limitation is particularly noteworthy because the impact of these materials during the use phase is substantial. It underscores the urgent need for further research to explore alternative raw materials that are more natural or innovative (Paiano et al., 2021) to mitigate the environmental consequences associated with paints. This research is imperative to minimise the negative effects of paints throughout their lifecycle, especially during their use phase, where their emissions have a pronounced impact on the environment.

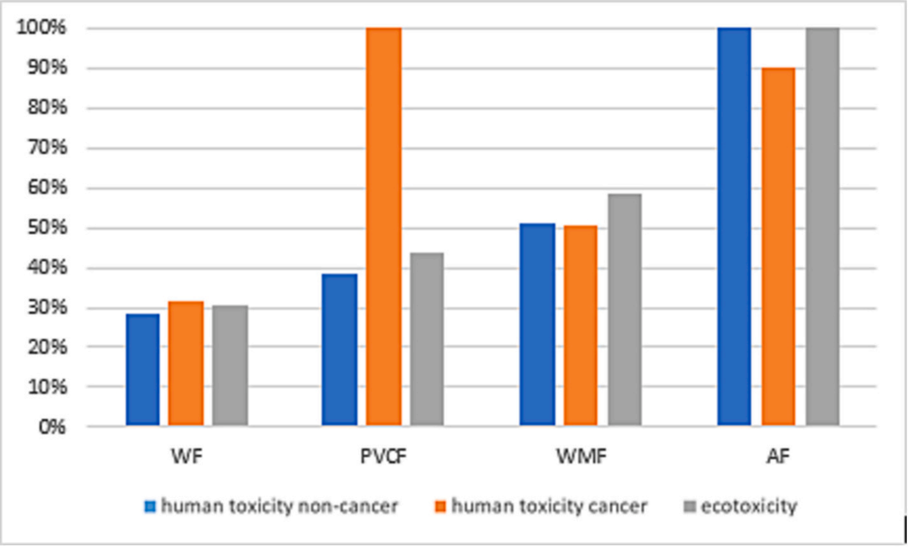
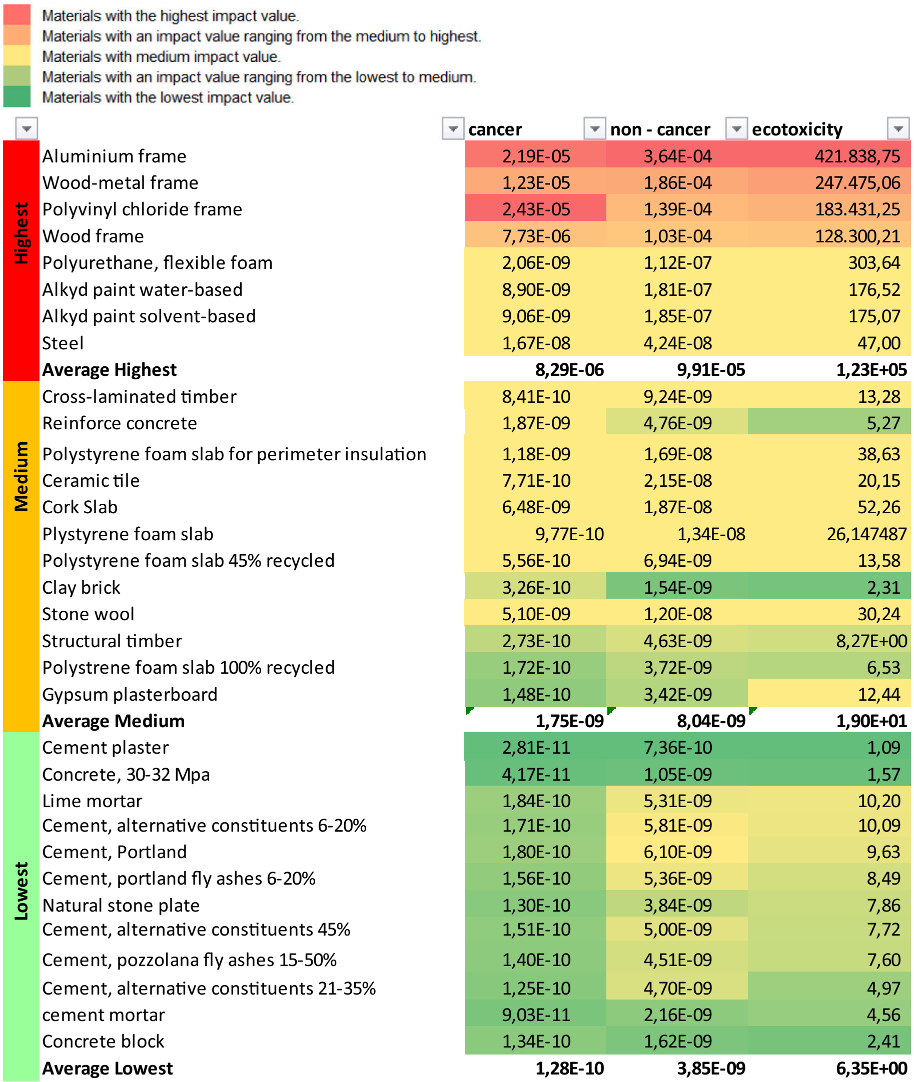


Fig. 7. Toxicity results for 1 m2 of windows frames with the same transmittance.

Table 9

Toxicity of materials divided into lowest, medium and highest.



🟥 Materials with the highest impact value.
🟧 Materials with an impact value ranging from the medium to highest.
🟨 Materials with medium impact value.
🟩 Materials with an impact value ranging from the lowest to medium.
🟩 Materials with the lowest impact value.

		cancer	non - cancer	ecotoxicity
Highest	Aluminium frame	2,19E-05	3,64E-04	421.838,75
	Wood-metal frame	1,23E-05	1,86E-04	247.475,06
	Polyvinyl chloride frame	2,43E-05	1,39E-04	183.431,25
	Wood frame	7,73E-06	1,03E-04	128.300,21
	Polyurethane, flexible foam	2,06E-09	1,12E-07	303,64
	Alkyd paint water-based	8,90E-09	1,81E-07	176,52
	Alkyd paint solvent-based	9,06E-09	1,85E-07	175,07
	Steel	1,67E-08	4,24E-08	47,00
	Average Highest	**8,29E-06**	**9,91E-05**	**1,23E+05**
Medium	Cross-laminated timber	8,41E-10	9,24E-09	13,28
	Reinforce concrete	1,87E-09	4,76E-09	5,27
	Polystyrene foam slab for perimeter insulation	1,18E-09	1,69E-08	38,63
	Ceramic tile	7,71E-10	2,15E-08	20,15
	Cork Slab	6,48E-09	1,87E-08	52,26
	Plystyrene foam slab	9,77E-10	1,34E-08	26,147487
	Polystyrene foam slab 45% recycled	5,56E-10	6,94E-09	13,58
	Clay brick	3,26E-10	1,54E-09	2,31
	Stone wool	5,10E-09	1,20E-08	30,24
	Structural timber	2,73E-10	4,63E-09	8,27E+00
	Polystrene foam slab 100% recycled	1,72E-10	3,72E-09	6,53
	Gypsum plasterboard	1,48E-10	3,42E-09	12,44
	Average Medium	**1,75E-09**	**8,04E-09**	**1,90E+01**
Lowest	Cement plaster	2,81E-11	7,36E-10	1,09
	Concrete, 30-32 Mpa	4,17E-11	1,05E-09	1,57
	Lime mortar	1,84E-10	5,31E-09	10,20
	Cement, alternative constituents 6-20%	1,71E-10	5,81E-09	10,09
	Cement, Portland	1,80E-10	6,10E-09	9,63
	Cement, portland fly ashes 6-20%	1,56E-10	5,36E-09	8,49
	Natural stone plate	1,30E-10	3,84E-09	7,86
	Cement, alternative constituents 45%	1,51E-10	5,00E-09	7,72
	Cement, pozzolana fly ashes 15-50%	1,40E-10	4,51E-09	7,60
	Cement, alternative constituents 21-35%	1,25E-10	4,70E-09	4,97
	cement mortar	9,03E-11	2,16E-09	4,56
	Concrete block	1,34E-10	1,62E-09	2,41
	Average Lowest	**1,28E-10**	**3,85E-09**	**6,35E+00**

4.7. *Windows frames*

For this comparative, the four most common types of window frame have been selected: wood (WF), PVC (PVCF), wood-metal (WMF) and aluminium frame (AF). To be effective, frames with the same thermal transmittance U = 1.6 have been selected. In the case of the wooden frame, the thermal transmittance is slightly better U = 1.5, but the difference is not so wide that it cannot be included in the comparison (Table 8) (Fig. 7).

In this case, we see that aluminium is the one that presents the greatest impacts; not only in the aspects of toxicity studied here, but we also know that it represents a very high demand for primary energy, as well as a GWP index also very high. Although we also know that these data improve when aluminium is recycled (Werner and Richter, 2000; Liu and Müller, 2012).

Second, we find PVC frames, which also have significantly high impacts. In this case, we also know that the consumption of water for its production is high. In this case, as other studies suggest, the comparison between the impacts of PVC and recycled PVC could be interesting, although we do not have these data in the database (Alsabri and Al-Ghamdi, 2020).

In the case of window frames, the data seem to indicate that the best option would be the wooden frame; with fewer associated impacts and better technical performance, in the design phase this should be the main option.

4.8. *Comparison between materials*

Finally, we also compared the different materials with each other, without considering the construction category. For this purpose, 1 kg has been chosen as the functional unit. To classify these materials, we have divided the table into three parts: the lower range, the middle range, and the upper range. Then, we have calculated the average for each range to observe the different levels of human toxicity cancer, human toxicity non-cancer, and ecotoxicity for each material. This has been represented through a colour graph ranging from green to red, with green corresponding to the lower range, yellow corresponding to the middle range, and red corresponding to the upper range (Table 9). This allows us to see that certain materials exhibit different impacts for the various categories. For example, reinforced concrete shows average values for both human toxicity cancer and non-cancer but has low values for ecotoxicity. Additionally, we can observe that ceramic bricks have a worse impact on human toxicity cancer compared to human toxicity non-cancer and ecotoxicity.

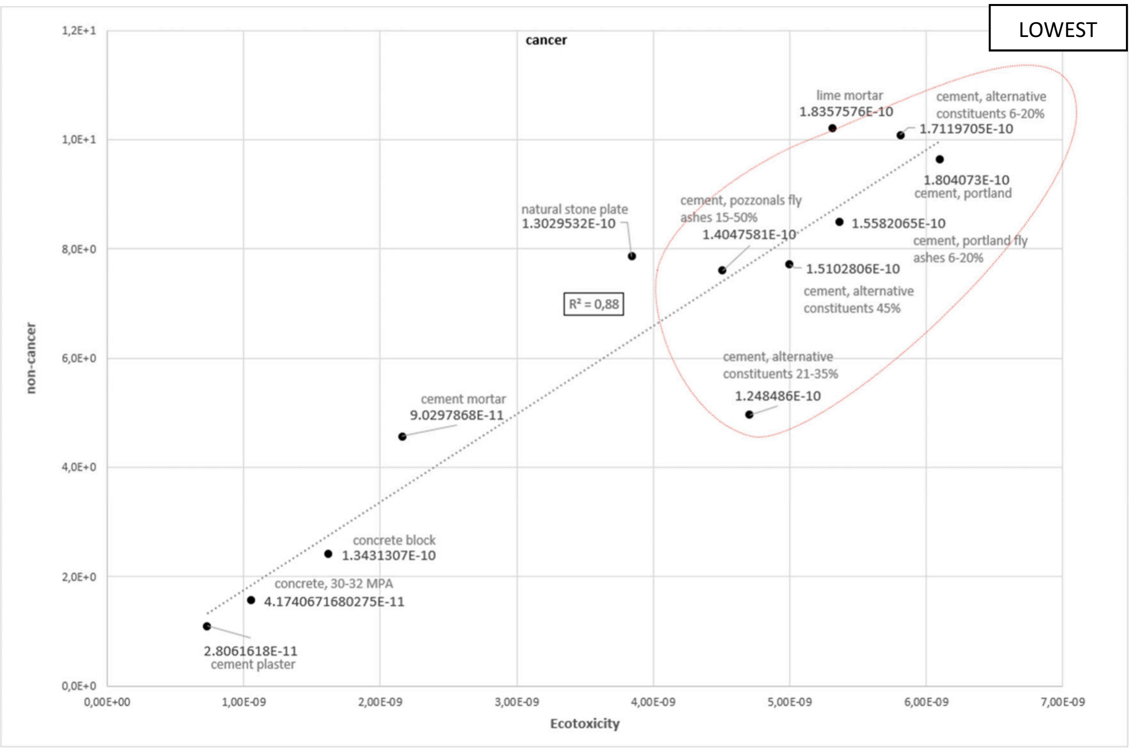


Fig. 8. Figure relating ecotoxicity to the non-cancer human toxicity category of materials with the least environmental impact.

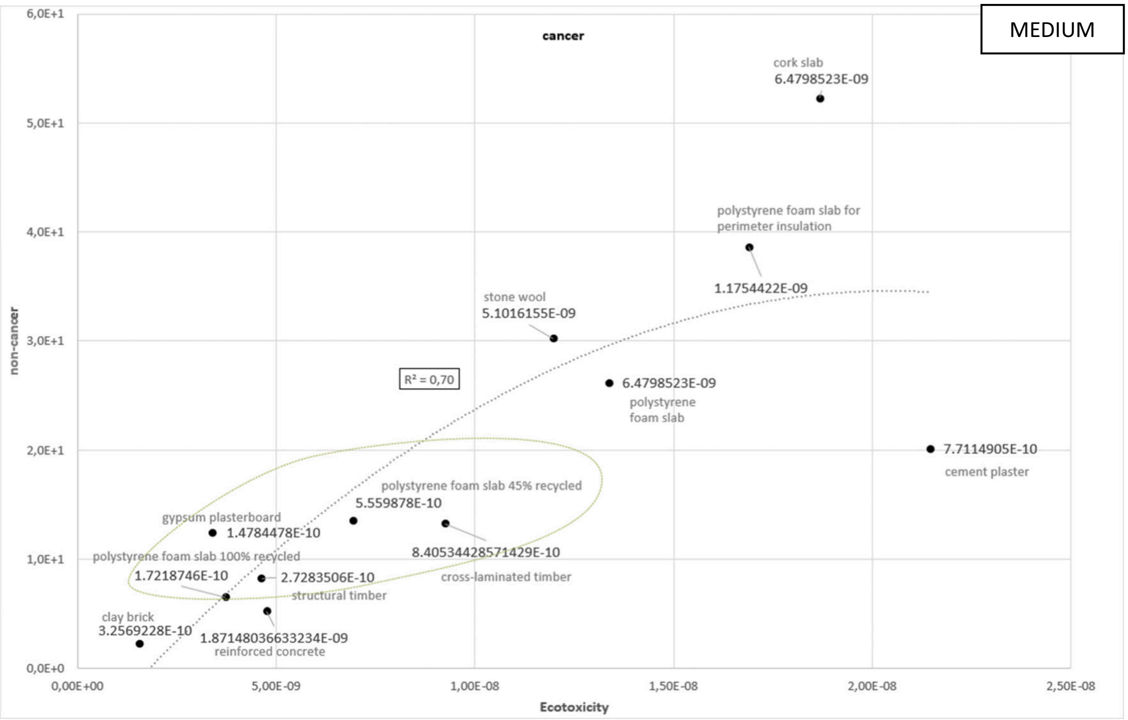


Fig. 9. Figure relating ecotoxicity to the non-cancer category for materials with a medium environmental impact.

These graphs aim to achieve two objectives: on one hand, identify patterns of behaviour among material families, and on the other hand, examine whether there is a correlation between human cancer and non-cancer toxicity with ecotoxicity.

With these results, we have created a chart for each category. The Figs. 8,9 and 10 represents 3 variables: human cancer, human non-cancer, and ecotoxicity. Several regression analyses have been conducted to examine the correlation between them and the R^2 coefficient.

In graph 8 we can observe the clustering of cement-derived products. Although the impact per kilogramme of these products may not be very high, it is important to consider that large amounts of them are used in a building, resulting in a significantly higher final impact. Additionally, it

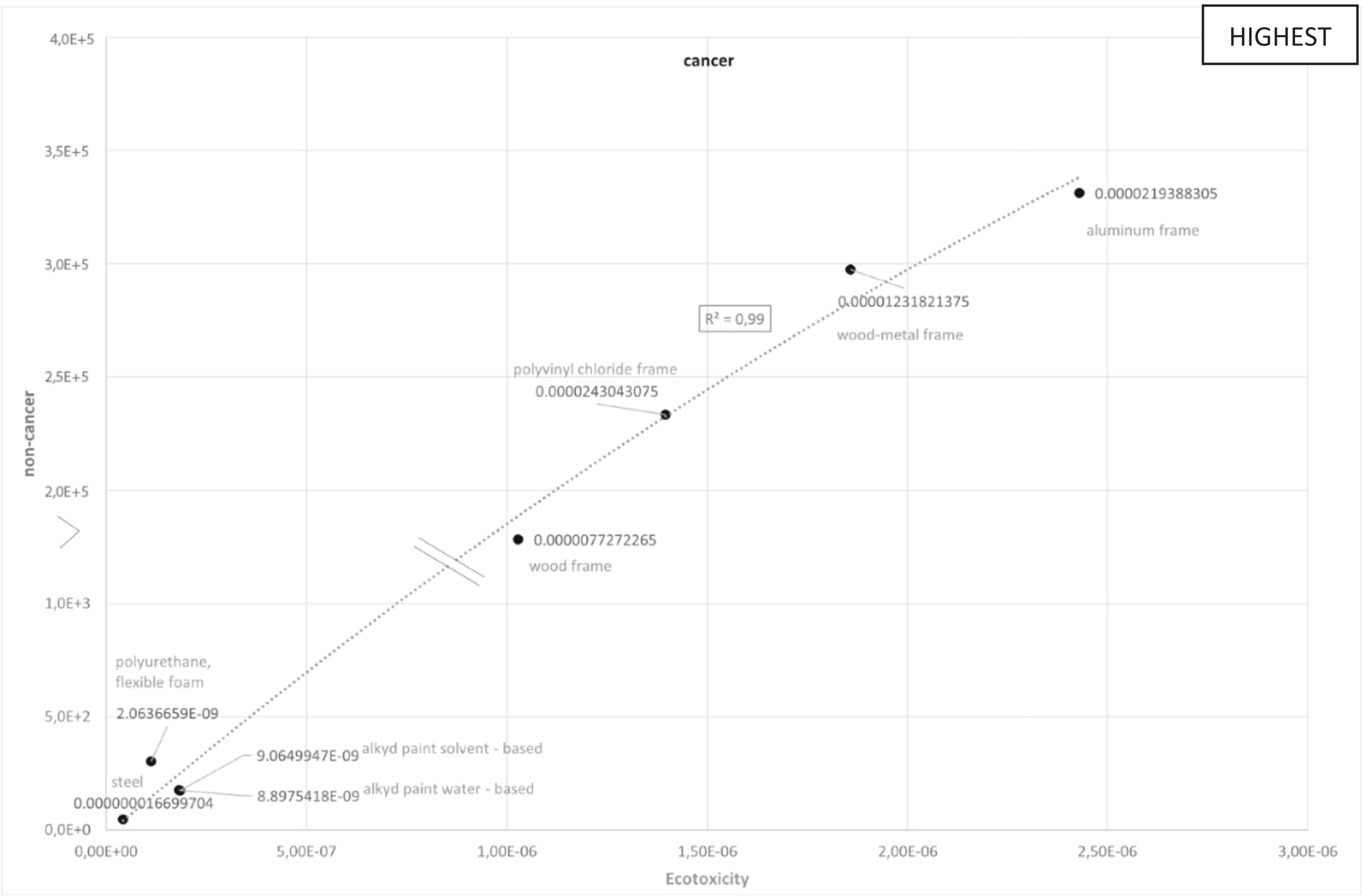


Fig. 10. Figure relating ecotoxicity to the non-cancer category for materials with the highest environmental impact.

can be noted once again that alternative aggregates (represented by the red circle) worsen the toxicity results.

On the other hand, in graph 9 we mainly find plastic derivatives, thermal insulations. In the lower part of the graph, in the green circle, we can verify that recycling polystyrene significantly reduces its toxicity. It is also worth noting that this graph includes both structural timber and CLT. As we pointed out earlier, although the impact per kilogramme may be higher, wooden structures tend to be lighter, so the final total impact is expected to be lower.

In graph 10, materials with a higher toxicity impact are shown: steel, polyurethane, paints, and window frames. We have previously mentioned the need to use other materials that are more environmentally friendly in the case of polyurethane and steel. The high environmental impact of window frames is mainly due to glass. Although the total weight of glass in a standard building is not significant, buildings with excessive glazing can have a greater environmental impact than expected.

4.9. Limitations

The objective of this analysis is to compare construction materials in terms of human toxicity and ecotoxicity. However, it is important to note that the databases are generic and do not have specific information from each country or manufacturer, which can generate distortions and make the data approximate. It would be ideal to have specific information provided by each manufacturer. In addition, in some cases, the information in the database may not be up to date, which can generate additional distortions. With this in mind, it is important to emphasise the relevance of new lines of research that propose methodological improvements, as well as continuing to improve the databases with which the researchers work. For this goal, collaboration is essential between all parties involved, both researchers and the industry sector responsible for developing and commercialising new products.

It is also important to note that the data obtained have been normalised and weighted, which means that the importance of each aspect may vary depending on the objectives of the life cycle assessment (LCA). In some cases, more importance will be given to aspects other than human health. As mentioned at the beginning of the article, it is important to have a holistic view of environmental impacts and not to sideline aspects such as human toxicity or ecotoxicity.

5. Conclusions and further research

Considering what has been discussed early on, when it comes to the choice of construction materials, it is important to have a broad perspective that considers various aspects, including toxicity, as these materials are used to build spaces where people live. Bearing this in mind, there are specific materials and material families that have been shown to be more harmful in this regard, so it would be advisable to avoid their use and opt for less harmful options for human beings. Among these materials, we mainly find insulation materials (specifically polyurethane) and paints. It is essential to consider this perspective when selecting these materials, so it is crucial to encourage innovation and the adoption of better techniques in production plants. This includes the substitution of harmful components with less harmful alternatives, as well as the promotion of the recycling and reuse of materials, provided that appropriate protocols are in place to assess their toxicity.

It is important to note that the evaluation of the toxicity of materials can be challenging due to the lack of homogeneous information and the variability of the criteria used in the studies. To address this issue, standardised criteria and protocols are necessary to assess material toxicity and promote the use of common databases and assessment tools. This would ensure that the results are comparable and reliable and would facilitate informed decision making about material selection.

Having inventory databases of construction materials that represent the construction reality of each country and specific industry data is fundamental. To achieve this, the use of type III (EPD) verified third-party ecolabels, based on life cycle assessment (LCA), should be encouraged. Currently, efforts are being made to expand the number of available EPDs, but complete information on toxicity-related impacts is required. Otherwise, impacts can only be evaluated approximately, making them difficult to adapt to different geographic contexts.

Ultimately, promoting research and development of new materials with lower toxicity and a more sustainable life cycle may be the best solution to reduce the need to compare and evaluate the toxicity of existing materials. This would encourage the adoption of safer and more sustainable materials in the future. In conclusion, a life cycle perspective should be applied and homogeneous tools and databases used to evaluate the toxicity of construction materials, allowing for more informed and accurate decisions regarding their selection.

This paper concludes by highlighting areas where further research could be conducted in the future. For example:

- Inventory databases for lifecycle assessments should be standardised to avoid skewing results according to the chosen database. This requires a wider coverage of materials and chemicals widely used in the construction sector and industry, in general.
- Improve LCA calibrations to avoid underestimating toxic emissions.
- Include data on the use phase of building materials.

CRediT authorship contribution statement

Belén Rey-Álvarez: Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **José Silvestre:** Conceptualization, Supervision. **Antonio García-Martínez:** Conceptualization, Supervision, Writing – review & editing. **Benito Sánchez-Montañés:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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