Journal of Cleaner Production 341 (2022) 130838

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Building material toxicity and life cycle assessment: A systematic critical review

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ARTICLE INFO

Handling Editor: Panos Seferlis

Keywords:
Toxicity
Building materials
Life cycle assessment (LCA)
Human health

ABSTRACT

This review systematically analyses the most relevant contributions published in the area of toxicity of building materials and their evaluation from the perspective of life cycle analysis to give a critical view of the relationship between the two fields. For this review, the systematic literature review methodology was chosen. With this methodology, it is possible to identify the most important sources and obtain a complete reading of the state of the question. The review shows that most articles on the toxicity of building materials focus on the usage phase, ignoring the life cycle perspective. On the other hand, the different Life Cycle Assessment methodologies start from different inventories, so the results will vary depending on the chosen method. In all cases, the predictions on toxicity are underestimated, so they are considered a secondary impact, and also the effects of bio-accumulation have not been integrated into the methodology. The main conflictive points found are discussed, such as the lack of coverage of substances widely used in the construction sector or the need to integrate new impacts.

1. Introduction

This document aims to review and provide a critical view between building materials and toxicity and how it has been evaluated from the perspective of the Life Cycle Assessment; toxicity is understood as the ability of a chemical substance to produce harmful effects when it comes into contact with a living being, and by extension, the environment in which it inhabits (Toxicidad | Definición | Diccionario de La Lengua Española | RAE - ASALE). For this, a critical review of the scientific literature related to both fields will be carried out.

It is well known that the construction industry represents around 40% of global carbon dioxide emissions (Global status report for buildings and construction, 2021), although it is true that between 2008 and 2019 an 18% reduction in CO2 emissions was achieved (Barker et al., 2018; Greenhouse Gas Emission Statistics - Air Emissions Accounts - Statistics Explained, n.d.). As Hu (2019) shows in his study, interest in zero-energy buildings has remained stable in recent years, while interest in sustabib_G_inable or green construction has been declining. This has led to the main interest being the reduction of energy, and more specifically operational energy (Soares et al., 2017), which accounts for between 80 and 90% of the total energy cycle. In this way, the design parts that include aspects such as human health and the relationship with the environment have been relegated to the background.

In order to have a holistic vision and optimize both the processes and the materials involved in the construction sector, it is necessary to use tools and methodologies that facilitate these analyses. One of the most used methodologies is the Life Cycle Assessment. This, unlike other methodologies, allows us to calculate the potential impacts of a product and/or process in all phases of the life cycle, from production to, ideally, recycling (ISO 14040:2006; ISO 14044:2006). In this way, the inventory of potential impacts is more complete, not focusing only on energy and the operational phase.

2. Study of toxcity of products through life cycle assessment

Life Cycle Assessment is one of the best methodologies for calculating and evaluating possible environmental impacts that currently exist (Integrated Product Policy - Environment - European Commission s. f.). Many modifications and improvements have had to be made to arrive at the current development of the methodology, which allows both a better prediction of the impacts and a better understanding by users of how to interpret the data and handle the methodology (Westh et al., 2015).

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https://doi.org/10.1016/j.jclepro.2022.130838
Received 5 August 2021; Received in revised form 31 January 2022; Accepted 3 February 2022

The evaluation of toxicity using the life cycle assessment has come a long way since the first publications. Guinée and Heijungs (1993) proposed the incorporation of toxic substances and the concept of a reference substance. Now, the latest publications focus on finding more precise prediction models, with a smaller uncertainty range and a greater representation of classified substances (Hou et al., 2020).

Currently, the CAS[1] (https://www.cas.org/) lists 70 million organic and inorganic substances, of which it is estimated that 100.000 may play a relevant role within the construction industry. Of these substances, only a small fraction is included within the different toxicity assessment methodologies (Jolliet and Fantke, 2015). The first categorization of toxic substances within the LCA framework contained only 181 substances (Huijbregts et al., 2000). To date, the USEtox model, the most complete in this field, includes 1250 (Rosenbaum et al., 2008).

However, the characterization of substances is not the only factor to take into account. It is also important to describe precisely how this substance is emitted during the different phases of the complete life cycle (Guinée and Heijungs, 1993). The time horizon that applies to different substances must also be correctly established, since some substances such as metals would need a virtually infinite horizon to accurately assess their degree of toxicity and their potential for contamination (Huijbregts et al., 2001). The need to distinguish in LCA between short-term and long-term issues is introduced (Hauschild et al., 2008).

All these factors have led to the development of different methodologies that seek the greatest representativeness with the least degree of uncertainty possible. These methodologies have differences between them, from the degree of importance of the different toxins and pollutants to the routes of exposure.

One of the first methodology developed was CalTox (McKone, 1993). This methodology is based on a spreadsheet that allows calculating and evaluating the risk to human health of being in contact with contaminated soil. This system makes it possible to predict concentrations of a toxin based on the time spent in air, water, the different soil strata, sediments, and plants.

Shortly after, the methodology called USES-LCA (Huijbregts et al., 2000) was developed. This system is based on the USES 2.0 system (Uniform System for the Evaluation of Substances), which in turn comes from the EUSES 1.0 (European Union System for the Evaluation of Substances) (Jbhj, Dt, y Eco 1997). This system updates the risk assessment for agricultural and non-agricultural pesticides.

This methodology establishes the analysis of 181 substances classified according to their emission: emissions to air, fresh water, salt water, industrial land and agricultural land. The results of the evaluation through these five categories were compared with the results of the evaluation through six more complex ones: freshwater ecotoxicity, seawater ecotoxicity, sediment ecotoxicity in freshwater, sediment ecotoxicity in seawater, ecotoxicity terrestrial and human ecotoxicity. Thus, they were able to verify differences of several orders of magnitude between the new calculated potentials and those previously calculated. This uncertainty, which can vary between 1.5 and 6 orders of magnitude, is due to the limitation of the parameters involved in describing chemical transport and degradation in both water and soil (Huijbregts et al., 2000a,b). The conclusion of the different studies published on this methodology is the need for a broader vision to be able to assess the true magnitude of the impacts (Huijbregts et al., 2001).

With different methodologies already published, immediately subsequent studies try to improve deficiencies that these first systems present. The number of evaluated substances is increased, and more emphasis is made on human toxicity, although it is only evaluated in the use phase (Hertwich et al., 2001).

However, the severity of health effects is so complex that it cannot be objectively assessed. In order to assess which consequences are more serious than others are, a survey that scores between 0 and 1000 different injuries and illnesses derived from toxic exposure is used (Landsiedel and Saling, 2002).

From this first approach, BASF (Badische Anilin - Und Soda-Fabrik) develops a methodology for calculating eco-efficiency (Saling et al., 2002). In this system, all the evaluated aspects are weighted (consumption of raw materials, energy consumption, resulting emissions, toxicity potential, and abuse and risk potential) and are represented as a single value. These values are placed on a two-way graph: environmental impact (normalized) and total cost (normalized). Thus, it introduces a new factor, the economic one, which makes it possible to evaluate the suitability of industrial products. To develop a more holistic view, modifications have been made to the model until a new method called SEEbalance, which includes social aspects (Saling, 2016). The purpose of this sum of all these factors represented by a single value graphically is to develop an application for quick decision-making and with great economic weight (Grosse-Sommer et al., 2020).

Among the uncertainties that the different methods present, one of the most studied is the geographical one. The calculation of the possible effects of toxins is highly dependent on the physical environment (Huijbregts et al., 2003). Based on this need and based on the USES 2.0 model, GLOBOX aims to increase the precision of the characterization factors related to environmental differences (Wegener Sleeswijk and Heijungs, 2010). It develops a very reliable methodology for countries with very homogeneous ecosystems, although the uncertainty in very large countries such as the US or China remains high (Wegener Sleeswijk and Heijungs, 2010).

With greater precision in terms of territorial characterization, the dispersion of toxins, both by air and by water, could be better predicted, which would greatly facilitate a reduction in pollution and an improvement in the management of environmental risks than the emission of these pollutants (Tian and Bilec, 2018). This level of precision is achieved with the IMPACT World + system, which makes it possible to evaluate emissions and consumption of natural resources anywhere in the world from four levels of characterization: global, predetermined continental, predetermined country and regional (Bulle et al., 2019). This study also highlights the need for greater ambition when analysing long-term impacts not only in the field of climate change, but also in the prediction of ecotoxicological impacts.

These differences between methodologies and the lack of consensus when evaluating human toxicity force researchers to decide which system is best for the study, depending on the strengths and weaknesses that each one presents (Pizzol et al., 2011).

To analyse the discrepancies between the different methodologies, numerous studies have been published that compare their operation and suitability according to the casuistry. One of these first comparisons is that of the CalTOX system with the WMPT (Waste Minimization Prioritization Tool) system (Pennington y Bare 2001). The CalTOX system is based on toxic equivalency potentials, while the WMPT calculates a single score (from 3 to 9) to buy impacts on human health based on three factors: persistence, bioaccumulation and toxicity. This study showed that both methods have very similar predictions but that the WMPT system would improve if the impact categories included were increased.

The CalTOX system has also been compared with the USES-LCA system, specifically, the differences in the intake fraction of one and the other (Huijbregts et al., 2005). The differences regarding the conceptualization of the territorial model, as well as the different proportionalities of the intake routes, mean that both systems give very different results between them.

Based on these comparative studies and the verification of the differences between one system and another, a scientific consensus model, USETox (Rosenbaum et al., 2008) was reached. This model is born from limiting the magnitude differences between the results obtained by the different systems, going from orders of 13 to a maximum of 2. In addition, this methodology proposes a protocol to be able to extrapolate

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[1] CAS is a division of the American Chemical Society that provides an authoritative collection of information on disclosed chemical substances.

routes of exposure, being able to go from oral intake to inhalation data. For this, the key mechanisms that influence human exposure are identified, one of them being population density in the case of inhalation (Rosenbaum et al., 2011).

Despite the clear contribution to the evaluation of toxic emissions that a model agreed between the different experts supposes, there are still many improvements to be made, both in the prediction of the behavior of some toxins, such as metals, or the geographical characterization (Henderson et al., 2011).

Not only have LCA methodologies been compared, comparative studies of LCIA have also been published to study how impacts are prioritized in each of them. The methods studied were: USETox, IMPACT 2002+ and ReCiPe (Mattila et al., 2011).

IMPACT 2002+ proposes improvements in the calculation of human toxicity and ecotoxicity, based on a change in the calculation of the calculated intake fraction. The transfer of pollutants into human food is no longer based on consumption surveys but on agricultural and livestock production data (Jolliet et al., 2003). On the other hand, ReCiPe is a method for evaluating LCIA that translates emissions and resource consumption into a reduced number of environmental impact scores using different characterization factors (Goedkoop et al., 2008).

These three models provide different data for the evaluations. On the one hand, the USETox model would give recommendations in a broader framework, while the other two methods focus on a few key contaminants (Mattila et al., 2011). As a final recommendation, it points to the importance of including bioaccumulation in LCA models.

Another challenge faced by the different methodologies is the integration of chemical sources produced by consumer products and building materials that have traditionally been excluded from the LCA (Csiszar et al., 2016). The correct evaluation of some toxins is also difficult. In the toxicity USETox model, the characterization is calculated based on the amount ingested in Kg. Regarding elements such as nanoparticles, this calculation method may be insufficient and underestimate its toxicity (Buist et al., 2017; Romeo et al., 2020).

The lack of characterization of many substances is an obstacle to evaluating these impacts correctly (Hou et al., 2020). This induces a lack of information in several of the aspects evaluated, producing a great difference between the reliability of some data and others (Dong et al., 2021). Although the data for emissions related to global warming are 98–99% reliable, for toxicity it is only 85%.

On the other hand, the different databases on which the Life Cycle Assessment are based are very different from each other, both due to the transparency of the data they show and the representativeness of the substances included. Some of these dissimilarities could be due to the difference in the manufacturing and obtaining of materials in some countries, but it would not explain the total difference between the results (Martínez-Rocamora et al., 2016).

All of this highlights the need to continue to improve the assessment and prediction of the different impacts within the LCA framework. In order to clarify this information, Tables 2–4, included in Section 5, summarize the different methodologies, identified gaps and improvement proposal described above.

3. Toxicity of building materials

Construction is one of the largest and most active sectors in the world, with no prospects that this trend will change (Global Construction Outlook to 2025, Q1 2021 Update, 2021). Within this sector, more than 100000 new chemical components have been developed since 1930, of which 95% of their toxic potential is ignored (Torgal and Jalali, 2011).

Table 1
Description of criteria to analyse bibliography.

TOPIC	SCOPE
Study of toxicity through LCA	categories studied new methodologies proposed
Toxicity of building materials Human health	life cycle phase

Table 2
Description of the different LCA methodologies analysed.

Methodology	Country	Approach	Reference
CalTox	United States	Calculation of risk of toxicity in humans by contact with contaminated soils	McKone (1993)
USES-LCA	Netherland	Analysis of 181 toxic substances Incorporation of chemical transport categories Calculation of uncertainty of the parameters	Huijbregts et al. (2000)
BASF	Germany	Calculation of eco-efficiency Introduction of enomic factors	Saling et al. (2002)
USETox	Scientific Consensus	Protocol to extrapolate data from different routes of exposure	Rosenbaum et al. (2008)
USES 2.0	Netherland	Improves the sensitivity of exposure to metals	van Zelm et al. (2009)
GlOBOX	Netherland	Increases the accuracy of geographic factors	Wegener Sleeswijk & Heijungs (2010)
SEEbalance	Germany	Introduction of social factors	Schmidt et al. (2004)

Table 3
Description of the different LCIA methodologies analysed.

Methodology	Country	Approach	Reference
Impact 2002+	Switzerland	Change in the calculated intake fraction calculation	Jolliet et al. (2003)
USETox	Scientific Consensus	Extrapolation of intake routes	Rosenbaum et al. (2008)
ReCiPe	Netherland	Characterization factors to score emissions and resource consumption	Goedkoop et al. (2008)
IMPACT World+	Switzerland	A globally regionalized life cycle impact assessment method	Bulle et al. (2019)

This difference between the compounds analysed and those included within building materials continues to increase, since there is an increasing interest in new materials with better mechanical properties and lower production costs (Mocová et al., 2019). To achieve these improvements, especially in products derived from cement, it is common to resort to non-conventional materials and, therefore, with unknown toxicity levels for which there are no adequate toxicity measurement protocols (Rodrigues et al., 2017).

With the identification of toxic potentials, usually encounter two problems are encounter:

- The lack of characterization of substances and their standardization.
- The lack of evaluation of the impacts of a substance throughout its entire life cycle.

3.1. *Characterization of substances and standardization*

For the supervision of chemical substances, (ECHA and n.d,) the European Chemicals Agency (ASALE & RAE, n.d.) was created in Europe, whose mission is to implement European Union legislation on chemicals. Within this legislation, there are different regulations that control the different categories of chemical substances and among which

Table 4
Gaps and improvements for LCA toxicity analysis.

Reference	Gaps identified	Improvement proposal
Guinée & Heijungs (1993)	Incorporation of potentially toxic chemicals	Incorporation of the reference substance concept HTP, TETP, EETP
Hertwich et al. (2001)	Do not identify any lack of information	Incorporation of HTP for 330 compounds
Pennington & Bare (2001)	Do not identify any lack of information	Comparison of the calculation of human toxicity between WMPT and TEP
Huijbregts et al. (2003)	The uncertainty in toxicity values depends on the geographical environment	Do not present any improvement proposal
Huijbregts et al. (2005)	Do not identify any lack of information	Comparison between CalTox and USES-LCA when calculating the intake fraction in humans
Hauschild et al. (2008)	Need to distinguish in LCA between short-term and long-term issues	Prediction model for 100-year emissions
Pizzol et al. (2011)	Lack of consensus when evaluating human toxicity Large differences in the results of the different methodologies	Do not present any improvement proposal
Mattila et al. (2011)	Inclusion of bioaccumulation in LCA models	LCIA, Impact 2000+, ReCiPe and USEtox model comparison
Hauschild et al. (2013)	Lack of toxic characterization Poor characterization of toxins Lack of characterization of geographical areas	Do not present any improvement proposal
Passer et al. (2015)	Lack of consensus and information regarding environmental statements	Do not present any improvement proposal
Csiszar et al. (2016)	Lack of integration in LCA of impacts produced by consumer products usually excluded	Integration into LCA of human health impacts including near-field chemical sources
Buist et al. (2017)	Difficulty in characterizing the toxicity of nanomaterials	Do not present any improvement proposal
Hou et al. (2020)	Lack of information on many chemicals	Proposal for machine learning models to estimate dangerous concentrations of ecotoxicide
Alejandrino et al. (2021)	Do not identify any lack of information	Inclusion of sustainable development goals in LCA

is the REACH (Registration, Evaluation, Authorization and Restriction of Chemicals). The purpose of this regulation is to protect human health and the environment, as well as to impose on companies the duty to identify and manage the risks derived from the substances they manufacture and market (Comprensión de REACH - ECHA,). A separate legal document was also introduced that specifically addresses the construction sector (Reglamento nº305, 2011). This document addresses the toxic emissions of materials in addition to more common aspects such as safety, stability, or mechanical resistance.

The main regulatory agencies of the world are the EU and the USA ones (ATSDR - Agency for Toxic and Disease Registry); thus, some investigators extrapolate the data from these agencies to third countries that have not so exhaustive data, so the results of the analysis, on some occasions, could be less accurate (Cucurachi et al., 2014).

In addition to globalization of data, another of the great challenges is to correctly assess exposure to chemicals and chemical mixtures. Gade et al. (2012) demonstrated that the REACH guidelines for chemical mixture calculation were valid; however, when comparing the results of the calculation and of the in situ measurements, it was found that in half of the cases the prediction was average and in the other half was underestimated. In this sense, REACH proposes exposure thresholds that are considered safe; these thresholds vary depending on the type of chemical substance and the effects on health. These exposure thresholds also apply to pollutants such as endocrine disruptors, which are increasingly present in indoor environments (Rudel and Perovich, 2009). As has already been stated, the prediction of the health effects of the combination of substances, known as the 'cocktail effect', is not reliable, so these thresholds should be revised downward to compensate for this effect (Zeliger, 2008).

The lack of normalization of many data and the variation between the prediction and the actual measurement derive cumulative errors that are transferred to different environmental assessment methodologies, such as Life Cycle Assessment, producing in many cases very serious underestimations of toxins (Kim et al., 2013; Slapnik et al., 2015).

This process is repeated since, if toxic emissions are underestimated in the calculation, other factors analysed will be given more relevance, such as the global warming potential, which in many cases leads to the search for new chemical compositions that reduce emissions contaminants, but which have not been exhaustively analysed from the point of view of toxicity (Maia et al., 2020).

3.2. *Assessment of toxicity in the different phases of the life cycle*

As Kobetičová and Černý (2017) state in their study, the trend of the Life Cycle Assessment is the reduction of emissions, which, to some extent, is reflected in the legislation. However, the trend in the development of new materials aims to improve their properties and reduce costs (Pacheco-Torgal and Labrincha, 2013). In this way, the objectives of energy consumption and the generation of greenhouse gases would prevail over other impacts such as ecotoxicity, classified in many cases as an additional impact (Dreyer et al., 2003).

Although the evolution curve for identifying toxins has been very pronounced in recent years, it needs to continue to improve and put more emphasis on direct exposure of workers to chemicals during the production phase and consumers during the use phase (Jolliet and Fantke, 2015).

The lack of studies of a specific material in all its life cycle phases accentuates the lack of information on the toxicity of said material during its use phase, since it is known that the toxicity can vary with the aging of the material (Cupi et al., 2015).

Therefore, when talking about human health in the context of building materials, it is inevitable to talk about indoor air quality and its effects on health (Jones, 2002a,b). In other words, for health purposes, indoor emissions can be more dangerous than outdoor emissions, since humans spend 90% of our time indoors and the degree of concentration outdoors is lower (Klepeis et al., 2001).

As early as 2011, Fisk et al. (2011) evidenced the benefits of improving indoor air quality in UK office buildings, estimating it at £ 20 billion. This shows that it is essential to include biohabitability criteria in the early phases of design and choice of materials, since this can prevent pathologies derived from poor design (Sarkhosh et al., 2021).

Different methodologies for the calculation of pollutants emitted by building materials during the use phase (Park et al., 2016) show that the impact on human health could be higher in the use phase than in the production and elimination stages because the use phase is underestimated (Skaar and Jørgensen, 2013), so prevention from the early design stages is essential. As early as 1982, Andersen proposed the replacement of toxic materials with less toxic ones within the framework of Danish regulations (Andersen et al., 1982).

Conventional building materials made from non-renewable resources are the main source of indoor air pollutants, even affecting outdoor air quality (Khoshnava et al., 2020). With an environmental design perspective, the substitution of conventional materials for other organic, natural and nontoxic ones, such as the substitution of cement for cob, would have the possibility of reducing both CO2 emissions and the toxic potential (Ben-Alon et al., 2021).

In Section 2 and 3 a description of the state of the art has been done, but a simple review of the literature is not enough in this case; it is necessary to provide an analysis that allows the identification of the niches of opportunity to continue improving this field of research. Therefore, the data described in the previous sections will be analysed, compared and discussed. For this, in Section 4 the methodology used for the selection of the bibliography will be described and in Section 5 the critical review of this will be included. Finally, Section 6 brings together the conclusions resulting from the critical review, as well as a section on possible future lines of research.

4. Methodology: systematic literature review

This systematic literature (SLR) review follows the methodology defined by Obrecht et al. (2020). It is a systematic and orderly procedure that makes it possible to identify the most important sources and obtain a complete reading of the state of the question. With this, it will be possible to answer a specific question from any field of research, in this case, the relationship between the toxicity of building materials and LCA. To do this, some keywords have been selected and then combined to obtain a more complete view of the research: 'LCA' AND 'TOXICITY', 'LCA' AND 'HUMAN HEALTH', 'LCA' AND 'BUILDING MATERIALS' and finally 'LCA' AND 'HUMAN HEALTH' AND 'BUILDING MATERIALS'. The databases chosen for these searches were Science Direct, Scopus and Web of Science.

Once the articles that appeared under these keywords were selected, a first screening of those that did not fit the theme was carried out by means of the title. A second screening was performed by reading the abstract and the remainder of the articles were read fully. In addition to these, other articles and book chapters were selected for their special relevance to the subject, because they are a common bibliography of the selected literature.

Concept maps were made through the R-Studio and Bibliometrix program, with its online interface, Biblioshiny. Some authors were connected to others, the most cited and relevant ones were identified in the year of their publication and cross-references were analysed in order to identify the groups of researchers, the most relevant authors and the most essential articles. This also allows us to identify the lack of connection between groups, revealing disjointed parallel lines. Thus, 127 articles have been identified as relevant for further classification (see Fig. 1).

To thoroughly analyse the bibliography and make a comprehensive study of it, the bibliography has been divided into three different categories, as can be seen in Table 1. These first categories have been established to understand the different ways in which toxicity is approached.

5. Discussion and further results

This study aims to analyse the relationship between toxicity and building materials and how this relationship has been approached from the Life Cycle Assessment. With the analysed literature, we can identify the conflicting points and which lines of future work should be followed.

5.1. *Analysis of the data from the toxicity study through the LCA*

In order to carry out a comprehensive study of the reference bibliography, the most representative tables have been made to classify the articles corresponding to the LCA bibliography. On the one hand, the classification of the proposed LCA methodologies (Table 2), those of LCIA (Table 3) and on the other hand, the articles that identify failures or proposals for improvement (Table 4).

In Table 2 the different methodologies have been summarized, already described in Section 2. These methodologies have been developed to calculate toxicity within the Life Cycle Assessment in order to proceed with their discussion. As can be seen in the comparison, the latest improvements that have been implemented are to upgrade the prediction capacity or to introduce new factors, but in no case to propose new detection protocols. In Table 3, which refers to the LCIA, the same thing happens. It is possible to see that there are improvements in the inventory of impacts, but the way these are valued is not modified.

In Table 4 can be found the articles that propose improvements or detect errors in the prediction of toxicity in the Life Cycle Assessment. Among these articles, some topics can be seen to be repeated, such as the need for a better characterization of toxic substances (Guinée and

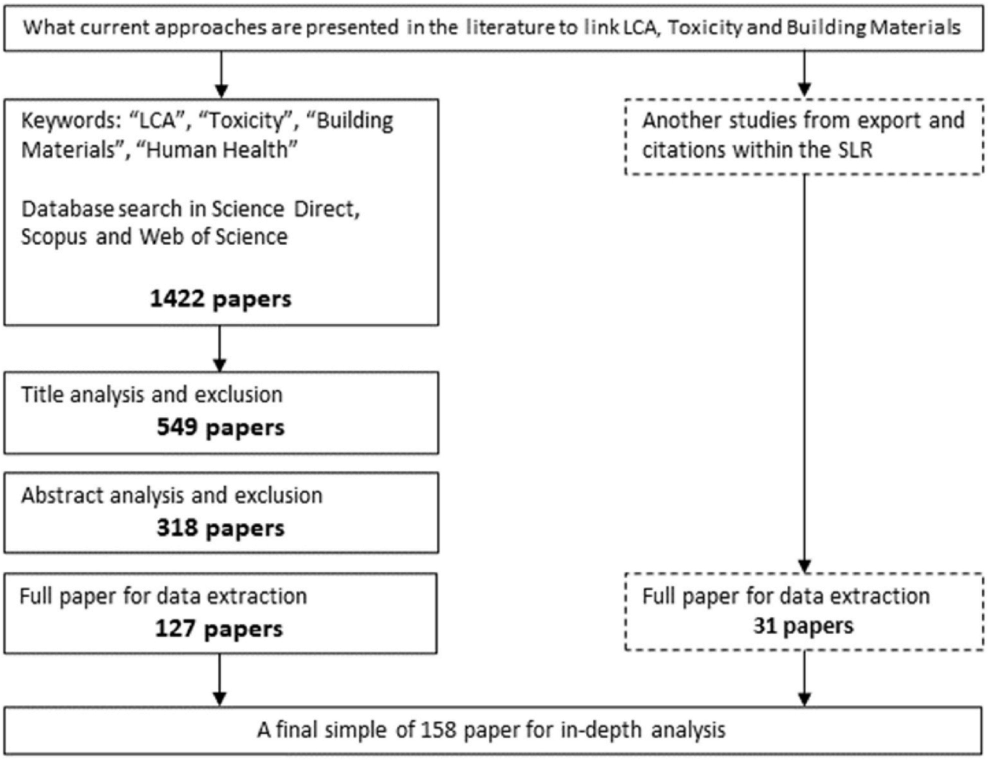

Fig. 1. Description of systematic literature review methodology.

Heijungs, 1993; Pizzol et al., 2011; Hauschild et al., 2013; Buist et al., 2017; Hou et al., 2020). These articles highlight the need to include in databases the most widely used toxic substances. Within this need, the need to incorporate bioaccumulation or interaction between toxic substances could also be included, as the toxicity results could change substantially (Mattila et al., 2011).

A second large identifiable group of articles refers to geographic uncertainty. Several articles speak of the need to improve geographic simulations in order to better predict the means of transport of chemical substances (Huijbregts et al., 2003; Passer et al., 2015; Hauschild et al., 2013; Csiszar et al., 2016). As can be seen in Section 2, this need has resulted in some specific LCA methodologies such as GLOBOX (Wegener Sleeswijk and Heijungs, 2010) and LCIA such as Impact WORLD + (Bulle et al., 2019).

Finally, there is a third group of articles that identify errors in the approach to toxicity from the Life Cycle Assessment (Buist et al., 2017; Hauschild et al., 2008; Passer et al., 2015; Pizzol et al., 2011). This is perhaps the most interesting group of articles, since the identified failures are not solved with an improvement of the existing methodology but with more profound changes in the methodology. As an example, the need to include longer-term impacts was found, which will improve the prediction of metal toxicity (Hauschild et al., 2008) or an emerging field such as the prediction of the toxicity of new substances such as nanomaterials (Buist et al., 2017).

All these needs should be considered when designing new chemical toxicity prediction protocols, in such a way that the new methodologies are adapted to the current constructive reality and to the sets of substances that this implies. In this regard, the LCA plays a fundamental role, since by adapting its methodology is possible to achieve a better prediction and a reading of this toxicity in all phases life of the material.

5.2. *Analysis of data from the study of toxicity in building materials*

As in the previous point, to make a comprehensive approximation of the reference bibliography, two summary tables have been made: the first is a classification by the materials on which the toxicity has been studied (Table 5) and the second is a classification of the toxic substances studied (Table 6).

In Table 5, a classification of the toxicity analysis for building materials can be seen. The building materials studied the most frequently are also the most common, materials derived from cement (Imbabi et al., 2012; Abdel-Gawwad et al., 2020; Almeida et al., 2021; Assi et al., 2018; Cheng et al., 2018; He et al., 2019; Holt and Berge, 2018; Lai et al., 2016; Lee, 2009; Li et al., 2016, 2021; Liu et al., 2021; Martins et al., 2021; Rafieizonooz et al., 2017; Shih et al., 2013; Stafford et al., 2016; Świerczek et al., 2021; Tosti et al., 2020) and ceramic materials (Andreola et al., 2019; Contreras et al., 2018; Cusidó and Cremades, 2012; Galán-Marín et al., 2010; Lin, 2006; Munir et al., 2021; Salleh et al., 2021; Ye et al., 2018). In both cases, the focus of the study was on the behavior of new additives in the mixtures. It can also be seen that, with one exception (Maia et al., 2020), toxicity studies of these materials are carried out exclusively for the production phase, without considering either the use phase, the longest, or the end-of-life phase. This leaves an incomplete perspective on how to evaluate the real performance of a building material.

Another widely studied group of materials are insulation materials (Andersen et al., 1982; Liang and Ho, 2007; Morin and Kubinski, 1978; Stec and Hull, 2011) and treated wood (Balasbaneh et al., 2018; Balasbaneh and Sher, 2021; Sotayo et al., 2020). In this case, it can be seen that the studies are not complete either, focusing on the use phase. In the case of insulation, in addition to the toxicity as a contribution of pollutants to indoor air, the contribution to fire toxicity in the event of a fire is also studied (Stec and Hull, 2011).

Paintings also accumulate much of the literature on the study of toxicity (Amara et al., 2018; Castritsi-Catharios et al., 2007; Gade et al., 2012; Ganguli and Chaudhuri, 2021; Gaylarde et al., 2021; Karlsson et al., 2006; Karlsson et al., 2010; Torres & De-la-Torre, 2021). This toxicity has been studied from various perspectives. The study of the toxicity of paints has been used as a control to find the difference between emitted and simulated particles (Gade et al., 2012). One of the most studied aspects is the search for less polluting alternatives (Amara et al., 2018; Castritsi-Catharios et al., 2007; Karlsson et al., 2006;

Table 5
Classification of toxicity articles by building materials.

Reference	Building material	Detection	Proposal	Life cycle phase		
				production	use	end of life
(Imbabi et al., 2012; Abdel-Gawwad et al., 2020; Almeida et al., 2021; Assi et al., 2018; Cheng et al., 2018; He et al., 2019; Holt and Berge, 2018; Lai et al., 2016; Lee, 2009; Li et al., 2016, 2021; Liu et al., 2021; Martins et al., 2021; Rafieizonooz et al., 2017; Shih et al., 2013; Stafford et al., 2016; Świerczek et al., 2021; Tosti et al., 2020)	Cement and concrete		New mixes	x		
Maia et al. (2020)		Lack of protocols to identify toxic additives	Methodology for evaluating the toxicity of new mixes	x	x	X
(Andreola et al., 2019; Contreras et al., 2018; Cusidó and Cremades, 2012; Galán-Marín et al., 2010; Lin, 2006; Munir et al., 2021; Salleh et al., 2021; Ye et al., 2018)	Ceramic materials		New mixes	x		
(Balasbaneh et al., 2018; Balasbaneh and Sher, 2021; Sotayo et al., 2020)	Trated wood		Comparative between different timber structure		x	
(Buist et al., 2017; Cupi et al., 2015; Ganguli and Chaudhuri, 2021; Li et al., 2016; Percebom et al., 2018; Pini et al., 2017; Romeo et al., 2020; Simeone et al., 2019)	Nanomaterials		Assessment of emergin materials		x	
(Ajabi Naeini et al., 2021; Gomes et al., 2018; Pacheco-Torgal and Jalali, 2012)	Rammed earth		New mixes	x		
(Andersen et al., 1982; Liang and Ho, 2007; Morin and Kubinski, 1978; Stec and Hull, 2011)	Insulation		Toxicity and fire toxicity		x	
(Amara et al., 2018; Castritsi-Catharios et al., 2007; Gade et al., 2012; Ganguli and Chaudhuri, 2021; Gaylarde et al., 2021; Karlsson et al., 2006; Karlsson et al., 2010; Torres & De-la-Torre, 2021)	Paint		Sustainable alternatives		x	
(Isnin et al., 2012; Kobetičová; Černý, 2017; Mølhave, 1982; Park et al., 2016; Rodrigues et al., 2017; Soares et al., 2017; Torgal and Jalali, 2011)	General			x		

Table 6
Classification of toxicity articles by pollutants.

Reference	Pollutant	Associated building material	Proposal	Life cycle phase		
				production	use	end of life
(Abdul-Wahab et al., 2015; Andersen et al., 1982; Becerra et al., 2020; Becher, 1996; Bernstein et al., 2008; Billionnet et al., 2011; Derbez et al., 2014; Desauziers et al., 2015; Fisk et al., 2011; Hulin et al., 2012; Jones, 1999; Langer et al., 2016; Paleologos et al., 2021; Roig, 2018; Sarkhosh et al., 2021; Smith, 2002; Spengler et al., 2001; Spengler and Chen, 2000; Weschler, 2001; Zhang et al., 2003)	Indoor air quality		Improve indoor air quality		x	
(Bai et al., 2020; Bentayeb et al., 2013; Cheng et al., 2015; Gross et al., 2017, 2003; Guo and Murray, 2001; Hodgson, Alfred T; Levin, Hal, Huang and Haghighat, 2003; Katsoyiannis et al., 2012; Kjærgaard et al., 1991; W. Liang et al., 2014; Mølhave et al., 1986; Rumchev, 2004; Sarigiannis et al., 2019; Seo et al., 2009; Lars, 1994.; X. Wang et al., 2008; Wei et al., 2012; Xu and Zhang, 2003, 2004; Yan et al., 2009; Yang et al., 2001; Zhang and Xu, 2003; Zhou et al., 2017, 2019)	VOC's	building materials			x	
(Guo et al., 2000; X. Liang et al., 2021)		adhesives based			x	
(Pohleven et al., 2019; Y. Wang et al., 2021)		wood			x	
Thevenet et al. (2018)		gypsum boards			x	
Andersen et al. (1975)	Formaldehyde	chipboard			x	
(Ezratty et al., 2007; Gunschera et al., 2013; Plaisance et al., 2014a, 2014b)		building materials			x	
(Weschler, 2001)	Endocrine disrupting	building materials			x	

Karlsson et al., 2010; Torres & De-la-Torre, 2021) as well as their contribution to the creation of microplastics (Gaylarde et al., 2021). In this case, in the analysis of the toxicity of the paints we can see that it is only studied in the use phase.

As in the previous point, it can also be seen here that the study of the toxicity of nanomaterials is an emerging field that occupies much of the most recent literature (Buist et al., 2017; Cupi et al., 2015; Ganguli and Chaudhuri, 2021; Li et al., 2016; Percebom et al., 2018; Pini et al., 2017; Romeo et al., 2020; Simeone et al., 2019).

In Table 6 the bibliography of the toxicity classified according to the pollutant to which they refer can be seen. The first large group of articles is the one that refers to indoor air quality (Abdul-Wahab et al., 2015; Andersen et al., 1982; Becerra et al., 2020; Becher, 1996; Bernstein et al., 2008; Billionnet et al., 2011; Derbez et al., 2014; Desauziers et al., 2015; Fisk et al., 2011; Hulin et al., 2012; Jones, 1999; Langer et al., 2016; Paleologos et al., 2021; Roig, 2018; Sarkhosh et al., 2021; Smith, 2002; Spengler et al., 2001; Spengler and Chen, 2000; Weschler, 2001; Zhang et al., 2003). In this case, not only a single pollutant is studied but also all those factors that intervene in indoor air quality, including humidity or thermal comfort. Therefore, the definition of sick building syndrome would also fall under this classification (Sarkhosh et al., 2021). As can be seen, in this case, when studying human health, the studies are limited to the use phase.

Among the pollutants themselves, volatile organic compounds (VOCs) is the group that accumulates the most bibliography, more than half (Abdul-Wahab et al., 2015; Becerra et al., 2020; Becher, 1996; Bernstein et al., 2008; Billionnet et al., 2011; Derbez et al., 2014; Desauziers et al., 2015; Hulin et al., 2012; Jones, 1999, 2002; Langer et al., 2016; Paleologos et al., 2021; Roig, 2018; Smith, 2002; Spengler et al., 2001; Spengler and Chen, 2000; Weschler, 2001; Zhang et al., 2003). In this case, it can be seen that the articles are classified by referring to the building material that can emit them, although this emission is only studied for the use phase. The next group of contaminants found is formaldehyde (Andersen et al., 1975; Ezratty et al., 2007; Gunschera et al., 2013; Plaisance et al., 2014a,b), which is associated in many cases with treated wood (Andersen et al., 1975).

As explained in point 4, one of the greatest concern pollutants are endocrine disruptors, due to their great effects with minimal exposure doses (Weschler, 2001). In this case, the bibliography related to building materials is very scarce. This represents a niche of opportunity to continue improving control regulations and thus prediction tools and methodologies.

5.3. *Approximation of toxicity through life cycle assessment*

In order to understand how toxicity has been addressed through the Life Cycle Assessment, it is essential to analyses the whole bibliography, in order to establish the appropriate relationships and connections, allowing us to fully understand the state of said relationship. To do this, and with the help of the Bibliometrix program mentioned above, the most needed and most clarifying graphs have been made. On the one hand, in Fig. 2 we have a graph of centrality and density, and on the other, in Fig. 3, a thematic relationship. Both graphics will be described below.

In this graph, there are two axes, one of centrality and the other of density. Centrality refers to the importance of the specific topic within the general scope and density refers to the development of the said topic. The size of the bubbles refers to the number of publications in this area.

In this case, it can be seen that the most important issues are those related to environmental pollutants and life cycle analysis. Human health issues and specific toxins such as VOCs are in second place. On the other hand, regarding the level of development of the topics, the most studied is the field of human health and life cycle analysis.

In this graph, it is possible to see how the different thematic blocks of the bibliography interact with each other. It is divided into four large blocks; LCIA related to impact categories, LCIA and its application to LCA, LCA applied to buildings materials and sustainable development. Looking more closely, it can be seen that there is no direct relationship between building materials and toxicity and that ecotoxicity outweighs human toxicity in the LCA field.

With this, we can verify the need to establish a relationship between building materials, toxicity and Life Cycle Assessment as a methodology, in order to have a holistic vision of the contribution of the construction sector to polluting and toxic emissions and to better understand how such toxicity affects building users.

6. Conclusions and future research

Life Cycle Assessment has many advantages in calculating impacts, including toxicity, compared to other existing methodologies. However, just because it could be the best method does not mean that it is perfect. As new materials are developed, the methodology will have to be adapted to make predictions as complete as possible.

This study provides a starting point for the study of the conflictive points of the Life Cycle Assessment methodology with respect to the

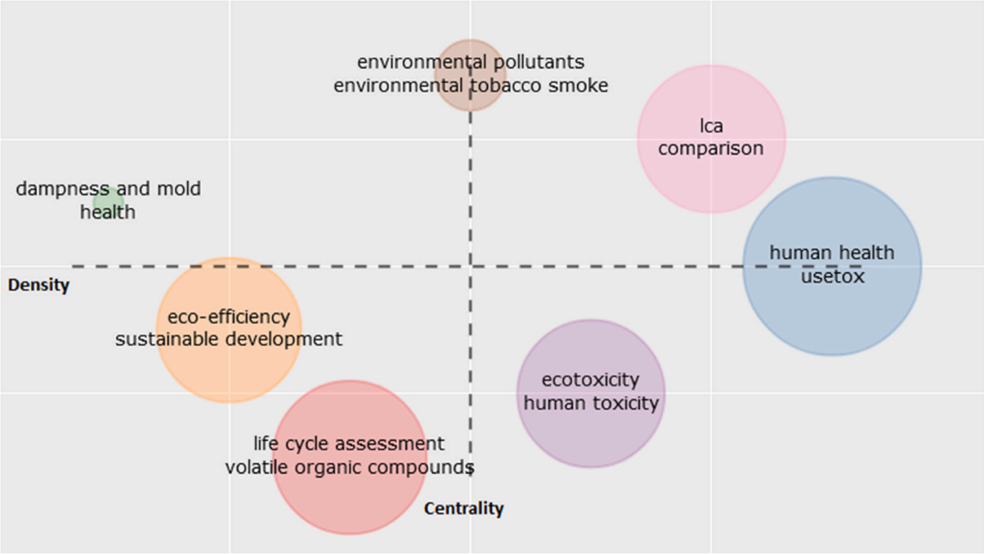

Fig. 2. Graph of centrality and density.

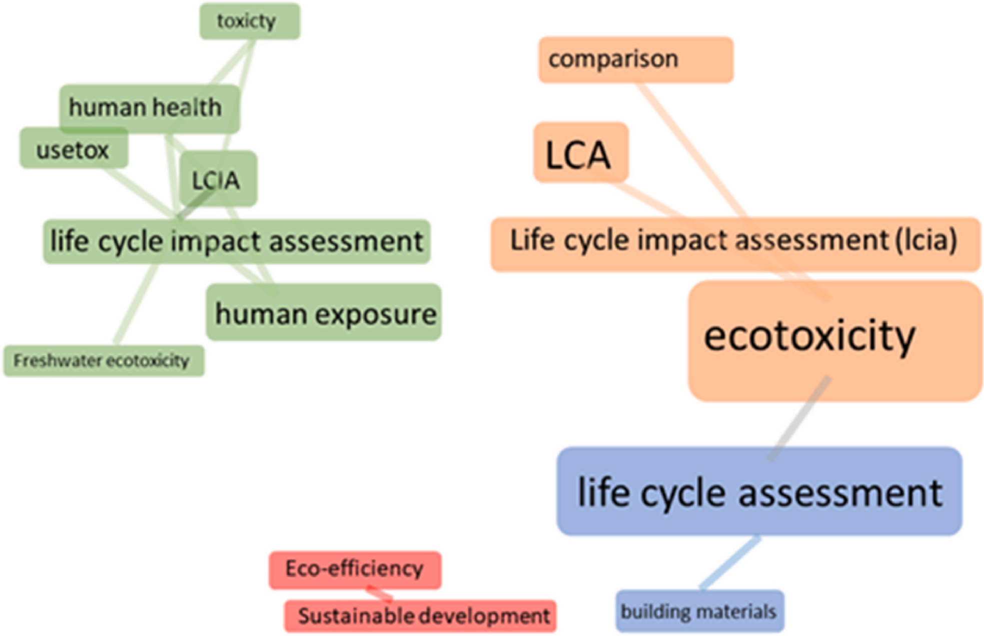

Fig. 3. Description of the interaction of topics.
Green: LCIA impact categories; Orange: LCIA application to LCA; Blue: LCA applied to building materials; Red: sustainable development.

analysis of toxicity, specifically of building materials. In order to effectively address the problem of toxicity and building materials, it is essential to do so from a life cycle perspective. This perspective makes it possible to analyse emissions in all phases of the life of the material, thus being able to control what impacts are produced, where, and what they are due to.

In addition, even though this relationship is fundamental, it has already been seen that it does not apply. However, in the LCA, human toxicity is an additional category that has received less weight, among other things, due to lack of control regulations and ignorance. Moreover, as for the analysis of the toxicity of building materials, as it has been analysed in the previous point, it is possible to see that they are not complete. On the one hand, if the analysis is done to evaluate the toxicity of the material, it can be found that it is limited to the production phase; on the other hand, if the pollutant itself is studied, almost entirely, it is limited exclusively to the use phase. Therefore, these analyses are partial and do not allow a material to be fully evaluated, so it is necessary that all toxicity evaluations be carried out in all the life phases of the material. This is corroborated by the lack of a bibliography that covers all phases of the life cycle of a specific material.

In addition, the development of new materials requires that the tools and methodologies used to measure toxicity be adapted to them. It is essential to include in the LCA protocols for the bioaccumulation and the interaction of different chemical substances, since the results of the cocktail effect can be considerably worse.

The foregoing allows us to conclude the nonexistent life-cycle perspective when calculating the toxicity of buildings materials. This is due to the fact that the trend in the development of materials and environmental application regulations has focused on reducing CO2 emissions, leaving other equally important aspects out of the equation.

This fact has been accentuated by underestimating toxic emissions, which gives more importance to other factors analysed.

This also results in a disconnect between regulations and scientific consensus in several respects. When a chemical compound is known to be harmful to health, it is not automatically transferred to the regulations, allowing that compound to continue to be used in a context as enduring as building. In many other cases, the precautionary principle is not applied, materials are shown to be toxic after the product has been developed, and in most cases adequate toxicity evaluation protocols are not available.

As it has been shown, the study of toxicity within the framework of life cycle analysis is an underdeveloped field of research that presents many interesting challenges. Future research will address how to unify these evaluation criteria, toxicity of building materials, and LCA, to be able to apply them from the design phase.

About future research, this article leaves conclusions some of the lines in which further research can be done, for example:

- Need to standardize the Life Cycle Assessment inventory databases to avoid distortions in the results depending on the chosen database. For this, greater coverage of chemical substances widely used in the construction sector and industry in general would be necessary.
- Include bioaccumulation and interaction protocols between different chemical substances in the Life Cycle Assessment.
- Improve the calibration of the Life Cycle Assessment so as not to underestimate toxic emissions.

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.

List of acronyms used in the study

ATSDR	Agency for Toxic and Disease Registry
CAS	American Chemical Society
ECHA	European Chemical Society
EU	European Union
USA	United States of America
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
REACH	Registration, Evaluation, Authorisation and restriction of CHemicals
VOC	Volatile Organic Compounds

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.130838.

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