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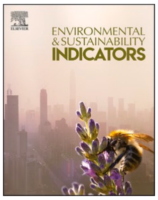

Environmental performance of refractories: A state-of-the-art review on current methodological practices and future directions

Sarah Badioli [a,b,1], Md Jubayed [a,c,1], Marielle Dargaud [b], Rinus Siebring [c], Angélique Léonard [a,*]

[a] *University of Liège, Chemical Engineering Research Unit, Agora Quarter, 11 Allée du 6 Août, 4000, Liège, Belgium*
[b] *Saint-Gobain Research Provence, Performance Ceramics and Refractories, 550 Rue Alphonse Jauffret, 84300, Cavaillon, France*
[c] *Tata Steel Netherlands, Ceramic Research Centre, Box 10.000, 1970 CA, Ijmuiden, Netherlands*

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ABSTRACT

The growing emphasis on sustainable industrial practices has intensified the need for environmental assessments of refractory materials, which are integral to high-temperature processes across sectors such as metallurgy, cement, and glass production. This review examines the application of life cycle assessment (LCA) and carbon footprint (CF) to refractories, providing an in-depth analysis of current practices, key challenges, and potential paths for improvement.

This review identified the system boundaries definition, the choice of the impact assessment methodology and the data quality as key methodological challenges driving the quality, accuracy, reliability and comparability of LCA studies. Recognising such challenges, this article advocates for standardised guidelines to enhance and homogenise methodological practices, guarantee cross-study comparisons, and efficiently support decision-making for sustainability. Additionally, transitioning from CF to LCA approaches is emphasised to avoid trade-offs across environmental impact categories. Lastly, establishing a collaborative network for data collection and sharing is fundamental to address the data quality criticality and enlarge the system boundaries both upstream and downstream. Finally, this review identified common trends in critical environmental domains and impacting processes.

Nomenclature

A	Alumina	LCM	Light Calcined Magnesia
AC	Alumina Carbon	M	Magnesia
AZ	Alumina Zirconia	MA	Magnesia Alumina
BFA	Brown Fused Alumina	MAC	Magnesia Alumina Carbon
CA	Calcined alumina	MC	Magnesia Carbon
CC	Cement Castable	MS	Magnesia Spinel
CH	Chamotte	MSC	Magnesia Spinel Carbon
D	Dolomite	MZ	Magnesia Zirconia
FB	Fibre Blanket	SM	Sintered Magnesia
FM	Fused Magnesia	TA	Tabular Alumina
IFB	Insulating Fire Brick	WFA	White Fused Alumina

1. Introduction

Refractories are ceramic materials that can withstand high temperatures and are resistant to severe service conditions characterised by corrosion and thermo-mechanical loading (Biswas and Sarkar, 2020). Refractory sidewall linings play the role of a protection layer to the metallic casing of industrial furnaces, whether as a chemical barrier or thermal insulation. They are indispensable for industrial sectors such as metallurgy, glass and cement production, power generation and petrochemical industry. To align with the goal of sustainable development, there is growing concern around the improvement of the environmental performance of high-temperature processes across the industry (Tang et al., 2019). The decarbonisation policy of the energy-intensive industrial sectors offers challenges and opportunities for the refractory manufacturers. Indeed, the refractory industry is required to develop

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* Corresponding authorQuartier Agora, B6A. 11, Allée du 6 Août, 4000, LIEGE, Belgium.
E-mail addresses: sarah.badioli@uliege.be (S. Badioli), md.jubayed@uliege.be (M. Jubayed), marielle.dargaud@saint-gobain.com (M. Dargaud), rinus.siebring@tatasteeleurope.com (R. Siebring), a.leonard@uliege.be (A. Léonard).

[1] Sarah Badioli and Md Jubayed contributed equally.

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less-impacting high-quality materials that are able to perform in the new operational conditions imposed by the sustainable transition. Thus, refractory makers are incentivised to improve both the behaviour in use and the environmental performance of their products over their entire life (Schnalzger et al., 2023; Boenzi et al., 2019). Besides the pressure from the end users, the global attention over the environmental performance of current economy and the stringent environmental regulations has already oriented refractory makers to adopt sustainability strategies. When green strategies are communicated to customers through explicit environmental labels and claims, rules must be followed to ensure reliability, transparency and to avoid greenwashing. Under the European Green Claims Directive (Ragonnaud, 2024), companies are obliged to demonstrate environmental claims with scientific evidence based on a life cycle perspective, i.e. quantifying the environmental burdens of products through life cycle assessment (LCA). Other examples of recent LCA-based regulated external declarations are EPDs and digital product passports (European Commission, 2022). Within this context, a boost in refractories' LCA is expected.

A significant number of assessments, in the form of carbon footprint (CF) and LCA, have already been performed on refractory raw materials supply and product manufacturing. Yet, to the best knowledge of authors, no review has been done on the topic. Hence, this review article aims to provide a comprehensive overview of the advancements, challenges, and future directions in the field of CF and LCA applied to refractories. The study is intended not only to guide LCA practitioners in the improvement of the methodological approach but also to support refractory specialists in eco-design and process optimisation. Indeed, by analysing the available LCA outcomes, this study provides insights into sustainable pathways for refractory manufacturing and waste management, ultimately supporting the industry's transition toward lower-carbon, resource-efficient operations.

The paper is structured into several sections: first, an introduction to environmental assessment methods and to refractories is proposed. Following, the review methodology is briefly discussed. Then, the detailed analysis of the literature is described following the LCA phases, namely goal and scope definition, inventory, life cycle impact assessment and interpretation. Lastly, the outlook chapter described the authors' conclusion on the direction of future research.

2. Overview of environmental assessment methods

2.1. Life cycle approach and product system characterisation

Life cycle assessment and carbon footprint are standard environmental evaluation tools based on the concept of life cycle. Life cycle thinking is the theoretical approach that addresses the three pillars of sustainability, namely the environmental, economic, and social consequences of a product or process throughout its life (Jacob-Lopes et al., 2021). Environmental Life Cycle Assessment (e-LCA), Life Cycle Cost (LCC), and Social Life Cycle Assessment (S-LCA) are the tools created to quantify the respective areas of sustainability. The life cycle approach was initially developed to focus on the environmental dimension, and it was only later expanded to include analysis of the other two pillars. Currently, the social dimension remains the youngest and least developed of the three (Pollok et al., 2021).

In e-LCA, from now on LCA, and carbon footprint (CF), the life cycle perspective helps avoid the displacement of environmental loads from one life stage of the product, or service, to another. Typically, product life cycle includes five stages, namely raw material extraction or acquisition, manufacturing and processing, distribution, use and retail, and end of life management. The collection of processes associated with the life steps of a product is called a product system. LCA is named cradle-to-grave if the system boundaries include all the phases from resource extraction to disposal, and cradle-to-cradle if it involves waste recycling. Cradle-to-gate LCA considers raw materials extraction and product manufacturing up to the gate of the plant. The smallest system boundaries are those of the gate-to-gate assessment, a partial LCA describing a single value-added process. Even though the cradle-to-grave approach is the best in terms of life cycle perspective, cradle-to-gate is more often chosen by companies as it is easier and faster.

The portion of the system specific to the product modelled is called foreground system, while the parts that reflect the industrial economy as a whole, such as the production of energy and commodities, constitute the background system (Kuczenski et al., 2018). The analysis of the product system requires the definition of the functional unit, or the quantified performance of the system, for use as a reference unit (ISO, 2006a). Functional units are foundational to LCA as they allow objective comparisons of different systems or products having the same function.

2.2. LCA and CF structure

LCA is a scientific, multi-step, multi-category decision support method that systematically analyses the potential environmental impacts of a product, or a service, over its entire life cycle (ISO, 2006a, 2006b). The effect on the environment is quantified on a set of impact categories representing environmental issues of concern, such as air, water and soil pollution, consumption of natural resources and the effects on organisms. Instead, carbon footprint estimates exclusively the total greenhouse gases (GHG) emissions of a product throughout its life cycle and relates such emissions to global warming potential and climate change. CF can be calculated through specific single-issue methodologies covering only GHG emissions or as a part of multi-assessment methodologies having a broader scope. In the latter case, carbon footprint could be considered a subset of LCA corresponding to the indicator for climate change.

A Life Cycle Assessment is made up of four phases (ISO, 2006b). First, the goal and scope phase entails the definition of the purpose, the structure and the methodological framework of the study. Following, the inventory analysis (LCI) involves data collection and calculation procedures to quantify relevant flows entering and leaving the product system. Then, the impact assessment phase (LCIA) consists in calculating the potential environmental impacts. LCIA comprises mandatory elements, namely classification and characterisation, and optional elements, namely normalisation and weighting (ISO, 2006a). In the compulsory steps, impact categories, category indicators and characterisation models are selected. Then, the indicators are calculated by assigning LCI results to the impact categories. LCIA optional steps refer to further elaboration of the results. Lastly, LCA results are interpreted, eventually reviewed and communicated.

LCA and CF can be performed for diagnostic or eco-design purposes. In companies, they are considered diagnostic tools when used to describe an existing product or process for both internal use and external communications. On the other side, they are considered as an eco-design tool when used to improve the future design of products or manufacturing route by directly influencing the product or process development (Farjana et al., 2021). Carbon footprint is widely used in companies, while the application of LCA is less common. The popularity of CF depends firstly on the lower complexity and the less data required. Moreover, the assessment of carbon emissions through CF is sufficient to be in line with the norms and compulsory reporting. Some authors stated that using CF in companies has initiated life cycle thinking and environmental assessments (Motta et al., 2022; Weidema et al., 2008).

2.3. Standards and guidelines

The literature demonstrates that environmental assessment results are highly affected by the assumptions and methodological choices, to the extent that different values can be obtained for the same product (Wang et al., 2018; Malabi Eberhardt et al., 2020). In Wang et al., the cut-off criteria and exclusion rules of the product system were identified as the most relevant assumptions (Wang et al., 2018), while in Malabi Eberhardt et al. and Ekvall et al. the effect of the allocation rules was discussed (Malabi Eberhardt et al., 2020; Ekvall et al., 2020). Dong et al. evaluated the inconsistencies caused by the application of different LCIA characterisation methods, hence facing a long-standing problem in the LCA community (Dong et al., 2021). The underlying differences in characterisation mechanisms and the derived impact categories often make the comparison of LCA results very difficult (Dong et al., 2021). Renou et al. concluded that global warming potential, acidification and resource depletion provided similar results with different LCIA methods, while significant divergences were observed for human toxicity and eutrophication (Renou et al., 2008). Additionally, Sena et al. emphasised the importance of aligning the geographical context of the system with the method's focus to ensure representativeness in regional or global conditions (Sena and Hicks, 2018).

In response to the need for consistency, transparency and comparability of LCA results, several protocols have been developed to harmonise the approach followed by the LCA practitioners. The reference standards are issued by the International Organisation for Standardisation (ISO). ISO 14040 and ISO 14044 are complementary standards describing, respectively, "principle and framework" and specific "requirements and guidelines" for LCA (ISO, 2006a, 2006b). Besides ISO compliance, if the purpose of the LCA is to produce an Environmental Product Declaration (EPD), the assessment must respect additional guidelines, be reviewed by a third party, and be published on an online platform. Specifically, it must conform to ISO 14025 (I.O. for S. ISO, 2010) and the eventual Product Category Rules, if existing. In 2012, the European Commission Joint Research Centre released the International Reference Life Cycle Data System handbook (European Commission. Joint Research Centre. et al., 2010) as a support for LCA consistency. More recently, the Commission proposed the Product Environmental Footprint (PEF) (European Commission, 2021). Despite the effort towards harmonisation, the variety of standards still limits the comparability of LCA results.

For single-issue methods, the mainstream reference guidelines are the ISO 14067 for the calculation and reporting of the carbon footprint (I.O. for S. ISO, 2018) and the Greenhouse Gas Protocol framework. The latter provides additional specifications to facilitate the quantification and public reporting of the Product Life Cycle GHG Accounting (WRI and WBCSD, 2011). It includes the classification of direct emissions (scope 1), electricity and heat indirect emissions (scope 2), and other indirect emissions (scope 3). Among the national standards, the British PAS 2050 (PAS, 2050, 2011) is widely used and is considered the first CF international standard. CF guidelines address carbon emissions topics, such as biogenic carbon and land use change, reducing the reliance of CF results on the assessment method compared to other environmental domains.

3. Introduction to refractories

Refractories are inorganic and non-metallic materials composed of, among others, oxides of silicon, aluminium, magnesium, calcium and zirconium and some non-oxide compounds like carbides, nitrides, borides, silicates or a combination of them. They are characterised by refractoriness, or softening point, of more than 1500 °C. Besides the resistance to high temperatures and thermal shock with volume stability and low creep, they show good corrosion, erosion and abrasion resistance at high temperature (Biswas and Sarkar, 2020).

Semler defined refractories as "the backbone of the industry" (Semler, 1991), due to their critical yet often overlooked role in the daily operations of almost every primary sector of finished goods manufacturing. Indeed, their unique properties make them irreplaceable enablers of the high-temperature processes, where they constitute the lining of vessels and furnaces. In 2016, the global demand for refractories was estimated to be approximately 45 million tonnes per year (Tamura, 2020). Around 70 % of this demand was attributed to the steel and iron industry (Boenzi, 2022). The refractory market is projected to grow due to the increased production in the consumer industries such as iron and steel, aerospace, electrical, and glass (Precedence Research, 2023; WRA et al., 2023). The economic expansion of the developing countries and their need for infrastructure and transport is considered to be one of the most relevant drivers of the industrial increase in activity (Precedence Research, 2023). Technical and technological innovations in consumer sectors may increase the refractory demand due to higher unit consumption. For example, steelmaking processes are transitioning to more sustainable routes, including hydrogen implementation and electrical smelting, which may pose greater challenges for refractories (Vert, 2023). Hence, the increase in refractory unit consumption in the steel sector is forecasted (Schnalzger et al., 2023; Ribeiro Gomes et al., 2024).

3.1. Classification and production routes

Refractories comprise a large variety of materials and are classified primarily on the basis of their chemical composition, physical form, and manufacturing route (Bhatia; Königshofer, 2012; European Refractories Producers' Federation, 2013; Kayama et al., 2008). Other classifications are available, but they are not discussed in this context. The categories and refractory products corresponding to the main classification methods are described in Table 1.

The chemical composition considers the chemical behaviour of the constituent materials. Basic refractories, such as those magnesia-based, are resistant to alkaline environments, while acid refractories, such as those silica-based, have the opposite behaviour and are resistant to acid environments. Neutral refractories are chemically stable in both acidic and basic conditions, and they are made of weakly acidic or basic materials such as zirconia and alumina. Regarding the physical form, it is possible to distinguish shaped refractories, or bricks, that are delivered to the user with a fixed shape, and monolithics, that are shaped by the user during the installation. Based on the installation method, monolithics can be further classified as castables, plastics, gunning mass, ramming mass, mortars, etc.

Refractories can be categorised according to their production route, as shown in Fig. 1. Monolithics belong to the "unformed" category and their manufacturing includes raw material supply and preparation, mixing and packing (European Refractories Producers' Federation, 2013; Kayama et al., 2008). Upstream phases are different for virgin and secondary raw materials. Virgin raw materials are obtained from minerals that are extracted, eventually purified, crushed and sent to

Table 1
Classification of refractories based on chemical composition, physical form, and manufacturing methods.

Classification method	Categories	Examples
Chemical composition	Acidic	Silica, zirconia
	Basic	Magnesia, dolomite
	Neutral	Alumina, chromite
Physical form	Shaped	Brick, block, special shape
	Unshaped (monolithics)	Mortar, castable, gunning mass, ramming mass
Manufacturing method	Shaping method	Hand-moulding, dry-pressing, casting, extrusion
	Thermal treatment	Tempering, sintering, melting
	Installation method	Casting, gunning, spraying, ramming

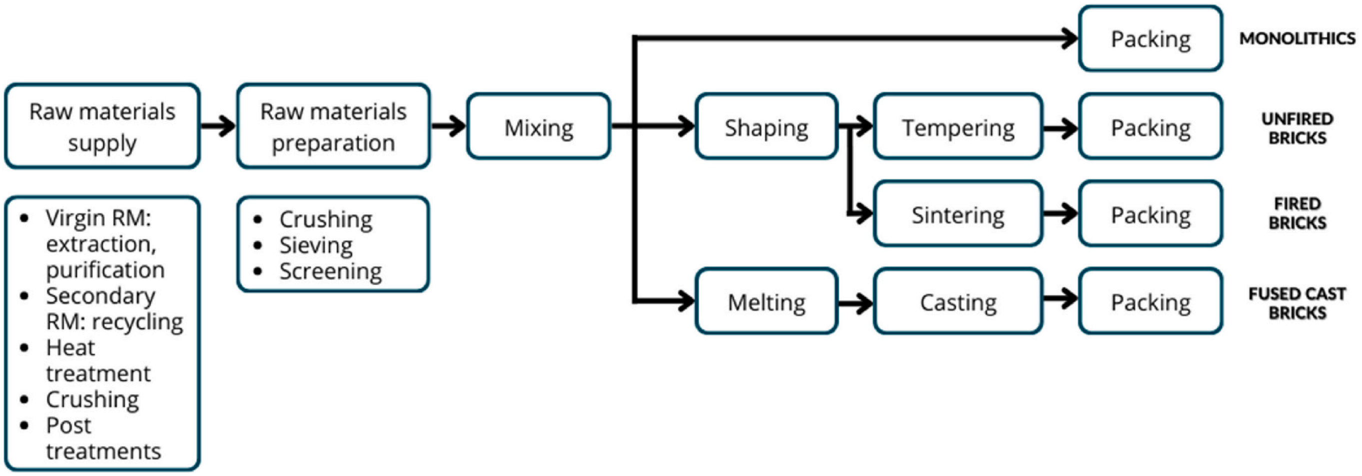

Fig. 1. Principal refractory production routes.

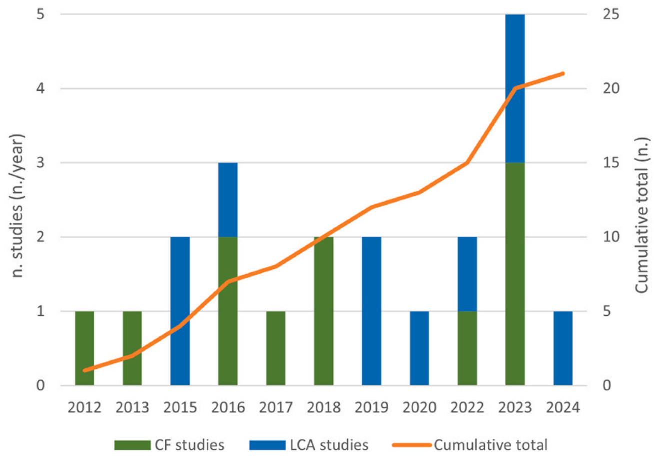

Fig. 2. Distribution of LCA and CF studies per year of publication.

treatment plants (Li et al., 2016). Indeed, they usually undergo sintering or melting, and crushing to be stabilised for high-temperature applications (Klaus et al., 2017). Instead, secondary raw materials are recovered from post-consumer scrap and/or waste through recycling treatments that usually include sorting and crushing (Horckmans et al., 2019). In comparison to monolithics, shaped refractories require at least two more steps, specifically shaping and heat treatment, and possibly post-treatments such as cutting and polishing (Kayama et al., 2008; European Commission, 2007). Different shaping methods exist, such as dry pressing, fused casting, hand moulding, injection moulding, hot forming, vacuum forming, etc. Also, three main types of high-temperature treatment can be identified, namely tempering, sintering and melting. After raw materials' preparation and mixing, tempered, or unfired, bricks undergo shaping and drying (around 110 °C) (European Refractories Producers' Federation, 2013). The latter stage is meant to reduce the water content in the refractory green body at a controlled rate via evaporation to prevent cracks or defects from appearing at high temperatures (Königshofer, 2012). The bricks are then tempered, or cured, at low temperature (200–400 °C). Fired bricks undergo intense thermal treatment in kilns just below their melting point (typically 1400–2000 °C) to consolidate and stabilise them (European Commission, 2007). Fused cast bricks use a different process route: the material is melted in an Electric Arc Furnace (EAF) and then cast into a mould.

4. Methods for the selection of literature

To carry out the screening of the available literature, a combination of keywords related to refractories and environmental assessment has been selected. Specifically, the environmental aspects have been described with: "LCA", "Life cycle assessment", "Life cycle analysis", "CF", "Carbon footprint", "environmental impact". Then, these words have been combined with "refractor*", "refractory brick", "fused alumina", and "magnesia".

The search was conducted in the period from December 2023 to June 2025, including the databases Google, Google Scholar, ScienceDirect, Scopus, and SpringerLink. The distribution of studies per year of publication is presented in the supplementary material. One of the most important steps of the screening process is to set up the screening criteria to reduce the list of articles and ensure all and only relevant studies are included. This screening approach is inspired by Thonemann et al. (2020). The following inclusion and exclusion criteria have been set:

Inclusion criteria:

- Documents that address the LCA of refractories and refractory raw materials.
- Documents that include the carbon footprint of refractories and refractory raw materials from a life cycle perspective.
- Peer-reviewed articles, conference proceedings, theses and reports are accepted as sources.

Exclusion criteria:

- Documents published before 2009.
- Reports or journal articles with pages less than three, posters and abstracts are not accepted as sources.
- Documents that address the LCA of raw materials not specifically intended for refractory application.

Twenty-one articles satisfy the inclusion criteria and constitute the literature portfolio analysed in this review. Fig. 2 shows the distribution of CF and LCA studies per year of publication, and the cumulative total over the years. Even though 2009 was set as a timeframe boundary for

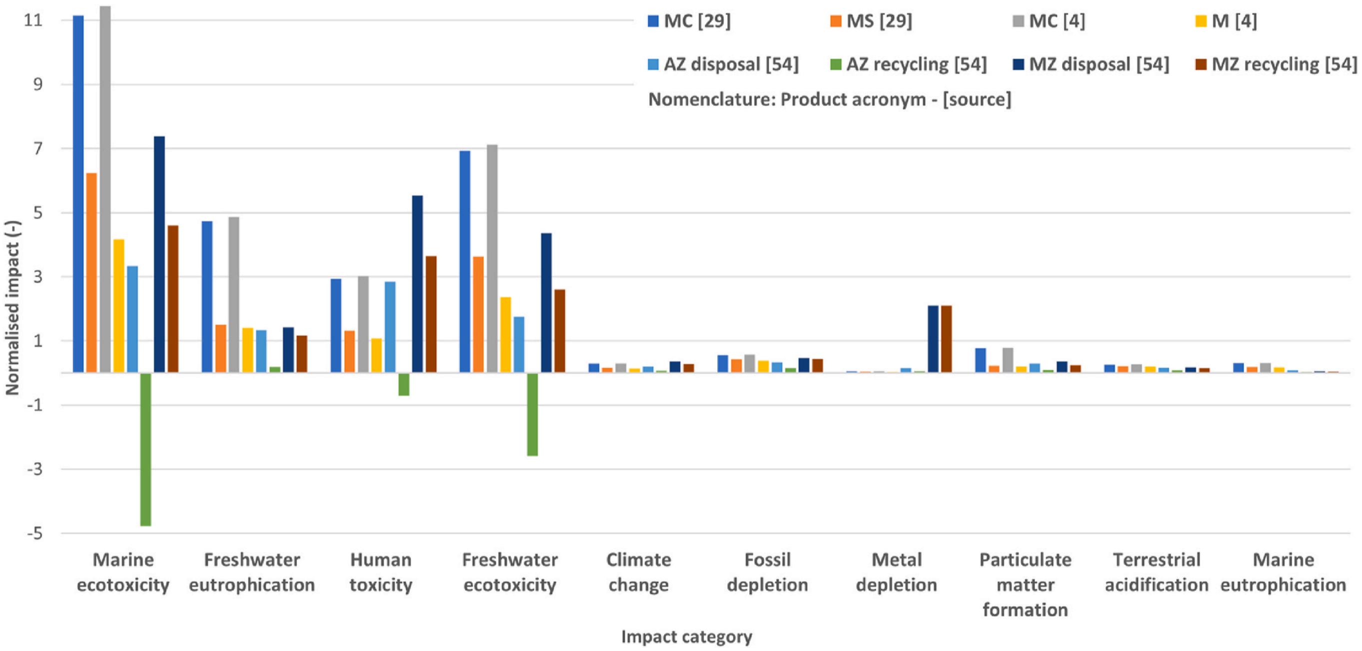

Fig. 3. Comparison of normalised results for the studies applying ReCiPe 2008 impact assessment method. Selection of the most relevant categories. Functional unit: 1t.

the selection of literature, no study was found for the period 2009–2011 (see Fig. 2).

5. Analysis of the reviewed studies

A thorough examination was conducted on the literature portfolio to address the methodological practices, data quality, transparency, and uncertainty associated with the results. Out of twenty-one studies, eleven calculated the carbon footprint (CF) of refractories and ten performed the life cycle assessment (LCA). Tables 2 and 3 summarise the main characteristics of the studies included in the present review.

The majority of the past research was focused on magnesia products, followed by alumina-based ones. The studies addressed both shaped and unshaped refractory products, most of which were designed for use in the steel industry. Some studies have been published within the same project; hence, they provide an overview of the progress of LCA modelling and results of the same product system. This is the case of the articles published by Boenzi et al. (Boenzi et al., 2019; Boenzi, 2022) and Muñoz (Muñoz et al., 2020; Muñoz, 2023).

Thirteen studies were conducted in Europe, while six, covering mainly raw materials production, referred to China. Variations are evident in the studies' set-up concerning goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2006b). A detailed analysis of models and approaches is presented in the subsequent sections by following the four-phase structure of LCA.

5.1. Goal and scope definition

The goal and scope of an LCA involve articulating its objective and intended application, defining the product system boundaries and outlining the main methodological choices.

5.1.1. System boundaries and functional unit

All the studies mentioned above defined the boundaries of their work in alignment with their objectives. Most documents (fifteen over twenty) overlooked operational and end-of-life management aspects: six articles focused on raw materials production, and twelve assessed the manufacturing of refractory bricks or castables. Of these, only three considered the use of the refractory in the steel industry (Boenzi, 2022; Muñoz, 2023; Henry-Lanier et al., 2016). In total, three studies integrated the end-of-life management by comparing waste management scenarios (Muñoz et al., 2020; Muñoz, 2023; Ferreira et al., 2015). Finally, only Muñoz followed a cradle-to-grave approach, investigating the entire life cycle of refractory bricks used in steel ladles (Muñoz, 2023).

Most studies addressed mining activities in their system, except few cases. Luong et al. (2018) argued the choice of previous authors of excluding mining activities from the product system because of the supposed negligible impact (Ren et al., 2016; An and Xue, 2017). The author concluded that such a hypothesis is invalid and leads to underestimated assessments. All studies addressed the major energy-intensive processes, such as calcination, sintering and melting, of raw materials processing and refractories production. Post-treatments like cutting, finishing, packaging activities, and waste treatment at production facilities were often neglected. None of the studies incorporated capital infrastructure, such as machinery and buildings, into their foreground system. About carbon footprint studies, differences have been noticed in the set of GHGs assessed. Königshofer only calculated CO_2 emissions (Königshofer, 2012), while An & Xue and An et al. took into account CO_2 and CH_4 emissions (An and Xue, 2017; An et al., 2018), and finally Ren et al. considered CO_2, CH_4 and N_2O emissions (Ren et al., 2016). In all other cases, the mention of $CO_{2,eq}$ suggested the inclusion of many GHGs, even though no details were given.

The predominant functional unit used in the reviewed studies was the "amount of product manufactured", typical of cradle-to-gate assessments. Henry-Lannier et al. stated that this choice might not be appropriate for systems including the use phase, as the functional unit should account for the product performance and function in the application (Henry-Lanier et al., 2016). This is particularly relevant when comparing the environmental performance of various materials. Indeed, Henry-Lannier et al. defined the functional unit as the quantity of material needed to line a tundish of known volume over one year (Henry-Lanier et al., 2016). Boenzi adopted the "amount (t) of steel produced" as a functional unit when comparing the environmental impacts generated using two magnesia bricks in a steel ladle (Boenzi, 2022). Initially, the LCA of refractory production was calculated per ton

Table 2
Overview of carbon footprint methodologies in the literature for refractory materials.

Reference	Materials	Inventory	Boundaries	CF standard	Sensitivity analysis	Uncertainty analysis	Geography
European Refractories Producers' Federation (2013)	Basic and non-basic fired bricks, pre-cast, basic unfired bricks, unshaped		RM, REF	GHG protocol			Europe
Königshofer (2012)	Basic and non-basic fired bricks, basic and non-basic unfired bricks, unshaped	X	RM, REF	PAS 2050			Europe
Ren et al. (2016)	LCM, SM, FM	X	RM	IPCC 2006			China
Henry-Lannier et al. (2016)	Bauxite fired bricks, bauxite castable, medium/low/ultra-low CC	X	RM, REF, U	NA			NA
An & Xue (2017)	LCM, SM, FM	X	RM	ISO 14044, 14067	x		China
An et al. (2018)	M, MC, MAC, MSC, MA and MS bricks	X	RM, REF	NA			China
Luong et al. (2018)	LCM	X	RM	ISO 14040, ISO 14044			Europe
Zhao et al. (2022)	FM, SM, LCM	X	RM	IPCC 2006, ISO 14067			China
Mottram et al. (2023)	FB, IFB, lightweight castable		RM, REF	(EN15804)[1]			Europe
Joos-Bloch et al. (2023)	Basic ramming mix		RM, REF	ISO 14067		X	Europe
Ranaivoharilala et al. (2023)	CH, Andalusite, WFA		RM	NA			Europe

Boundaries: RM Raw materials production; REF refractory manufacturing; U refractory usage; EOL end of life management.
NA not available.[1] The reference standard is not clearly stated, and EN15804 is only mentioned to explain LCA principles.

Table 3
Overview of LCA methodologies in the literature for refractory materials.

Reference	Materials	LCI	Boundaries	Functional Unit	LCIA method	Impact categories	Uncertainty analysis	Sensitivity analysis	Geography
Ferreira et al. (2015)	AZ, MZ	X	EOL	1 kg waste management	ReCiPe 2008	18 categories			Europe
Li et al. (2015)	LCM, FM	X	RM	1 t material produced	CML 2001-Nov.2010	11 categories		x	China
Özkan et al. (2016)	MS Brick	X	RM, REF	1 t material produced	CML-IA baseline (v.3)	11 categories		x	Europe
Boenzi et al. (2019)	MC and MS bricks	X	RM, REF	1 t material produced	ReCiPe H 2008	18 categories			Europe
Tang et al. (2019)	AC bricks	X	RM, REF	1 t material produced	ReCiPe H 2008	18 categories	x	x	China
Muñoz et al. (2020)	MC bricks, various shaped (A, M, Z), M monolithic	X	EOL	1 t waste management	NA	4 categories	x	x	Europe
Boenzi (2022)	MC and MS bricks	X	RM, REF, U	1 t steel produced	ReCiPe H 2016 (1.1)	18 categories			Europe
Muñoz (2023)	Unshaped M, D, CH. Shaped MC, A, CH.		RM, REF, U, EOL	1 million t steel scrap molten per year	Stepwise method[1]	14 categories			Europe
Canton et al. (2023)	BFA and TA ultra-low CC		RM, REF	1 t material produced	CML, IPCC and EF	11 categories			Europe
Badioli et al. (2024)	LCM, FM, CA, WFA	X	RM	1 t material produced	EF3.1	13 categories			China

Boundaries: RM Raw materials production; REF refractory manufacturing; U refractory usage; EOL end of life management.
Standards: NA not available.
[1]Method developed by 2.-0 LCA consultants.

produced. Then, the system boundaries and the functional unit were adapted to include the use phase. A theoretical formulation for shifting the impacts from the bricks reference unit to the steel functional unit was provided. In a similar context, Muñoz selected "amount of (steel) scrap melted per year" as a functional unit to assess the impacts of refractories used in a steel ladle (Muñoz, 2023). Regarding the end-of-life LCAs, both Muñoz et al. and Ferreira et al. chose as a functional unit the "amount (t) of refractory waste managed" (Muñoz et al., 2020; Ferreira et al., 2015).

5.1.2. *Allocation approach*

Allocation challenges related to multifunctionality and recycling loops are common in life cycle assessment. None of the articles included in this review documented the generation of co-products from any process within the scope of their study; hence, no multifunctionality was reported. Regarding recycling loops, Muñoz et al. and Ferreira et al. applied the zero burden assumption to the recycling activities (Muñoz et al., 2020; Ferreira et al., 2015). In other words, refractory wastes do not carry the burden of the waste generation process and have no environmental impact on it. The environmental benefits of recycled products were accounted for through a "system expansion with substitution" approach for both closed-loop and open-loop recycling. The choice is coherent with the aim of comparing waste management options.

5.2. *Inventory*

In this stage, research faces hurdles associated with the availability and quality of data. Obtaining sufficient inventory data proves to be particularly challenging due to the absence of historical data and the confidentiality relative to industrial processes. Most of the analysed papers reported inventory either in the main article or in supplementary information, except for some studies conducted by manufacturers due to confidentiality and data sensitivity (European Refractories Producers' Federation, 2013; Muñoz, 2023; Mottram et al., 2023; Joos-Bloch et al., 2023; Ranaivoharilala et al., 2023; Canton et al., 2023). The foreground

LCI data were collected from various sources, including direct measurements, stoichiometric calculations, literature, suppliers, and expert opinions. Stoichiometric relations were mostly used to estimate direct GHG emissions, while approximation and estimation were necessary to model emerging products. Background data were usually sourced from commercial databases, most commonly ecoinvent (Wernet et al., 2016) in the cut-off version. Coherently with the consequential LCA approach, Muñoz used the consequential version of ecoinvent in Muñoz et al. (2020), then substituted with Exiobase (Stadler et al., 2018) in Muñoz (2023). Existing databases have limited information relative to refractories and their raw materials. They often rely on old sources or approximations from similar processes. For example, the ecoinvent datasets of refractory bricks are built upon primary data collected in 1999 (Kellenberger et al., 2007), while the magnesium oxide dataset is approximated from lime processing (Hischier, 2007) and updated with primary values for energy, water and GHG emissions from European Commission (2013). These approximations are worthy of providing foundational data for the inventory, but risk overestimating or underestimating actual processes, potentially altering the LCA results. Indeed, estimations could generate low-quality data in terms of technological, temporal, and geographical representativeness of a product or system (Lam et al., 2020). Data quality is a matter of concern as it directly influences the credibility, robustness and reliability of LCA outcomes. Only in two studies data quality was clearly assessed (Königshofer, 2012; European Refractories Producers' Federation, 2013). Temporal and geographical inconsistencies were common issues among the reviewed studies. For instance, Ranaivoharilala et al. compared the carbon footprint of various alumina-containing materials calculated on in-house data from 2021, with that of calcined alumina based on literature data published a decade earlier (Ranaivoharilala et al., 2023). In parallel, several studies conducted in Europe relied on Chinese data for raw material processing without specifying whether these materials were procured from China (Boenzi et al., 2019; Boenzi, 2022; Muñoz et al., 2020).

5.3. Life cycle impact assessment

The life cycle impact assessment phase consists of the classification and characterisation of all substances in the life cycle inventory to quantify their relative contribution to environmental impact categories. In the selected literature, diverse impact assessment methodologies were chosen, with ReCiPe being the most used one, even though it was applied in different versions (Goedkoop et al., 2013; Huijbregts et al., 2017). The selected LCAs address between four and eighteen impact categories. Global warming potential, acidification, eutrophication, and fossil resource consumption were common to all studies. In some cases, a mix of impact categories from different methods was created to adapt the assessment to the LCA scope and the product system challenges. For instance, Canton et al. combined 10 impact categories from ReCiPe, IPCC and EF methods (Canton et al., 2023). Muñoz referred to 14 impact categories developed within the Stepwise EPD project, but did not indicate the methodology associated with each category (Muñoz, 2023). In Muñoz et al., the results were shown with no mention of the characterisation factors or assessment methods (Muñoz et al., 2020).

None of the studies compared alternative LCIA methods, despite the potential influence on the results of some impact categories (cf. 2.3 Standards and guidelines). However, Boenzi and Li et al. provide characterisation results for various LCIA methods in the supplementary material, despite the lack of interpretation of such results (Boenzi, 2022; Li et al., 2015). All papers presented results with absolute values. Only three references applied normalisation (Tang et al., 2019; Li et al., 2015; Özkan et al., 2016) and none of them applied weighting.

The impact assessment step is different when calculating products' carbon footprint. As already mentioned, CF can be quantified either as the sum of direct and indirect GHG emissions of a product system or as LCA-based GWP. In the first case, CF standards rule the choice and calculation of GHG emission factors for materials and energy. Ren et al. and Zhao et al. followed the IPCC Guidelines for National Greenhouse Gas Inventories (Ren et al., 2016; Zhao et al., 2022; Eggleston, 2006). Königshofer's approach was compliant with the PAS 2050 (PAS, 2050, 2011; Königshofer, 2012), while PRE's report was in line with the GHG Protocol Product Life Cycle Accounting and Reporting Standard (WRI and WBCSD, 2011; European Refractories Producers' Federation, 2013). An & Xue, Luong et al. and Joos-Bloch et al. referred to the general ISO standards ISO 14040, 14044, and 14067 for the definition of carbon footprint (An and Xue, 2017; Luong et al., 2018; Joos-Bloch et al., 2023), while no standard was mentioned by Henry-Lannier et al. and An et al. (Henry-Lanier et al., 2016; An et al., 2018). In two cases, CF seemed to be LCA-based, even though not clearly stated. Indeed, Mottram et al. referred to the GWP of the EN15804+A2 standard (Mottram et al., 2023; CEN/TC 350, 2019), while Ranaivoharilala et al. only mentioned the GWP100 indicator with no reference to the methodology (Ranaivoharilala et al., 2023).

5.4. Interpretation

The 4th phase of LCA is the interpretation of LCIA results, evaluating them against the goal and scope to produce conclusions and recommendations. It includes hotspot identification and discussion of the cause and effect behind the results. Interpretation is supported by sensitivity analysis, which estimates the influence of key input parameters on LCA results, and uncertainty analysis, which evaluates the variability of results due to uncertainties' propagation.

5.4.1. Identification of critical environmental domains

Normalisation is an optional step in LCA studies that involves dividing the characterisation results by normalisation factors, i.e., values representing the total impact of a reference region for a certain impact category (European Commission, 2017). As normalised results have a common measure unit or are dimensionless, they facilitate direct comparison across different impact categories, thereby allowing the identification of the most significant environmental burdens. Such a comparison is not possible on characterisation results due to the variety of measure units used. The most impacted categories are characterised by the highest normalised impacts. In the case of refractories, only three of the analysed articles provided normalised results (Tang et al., 2019; Li et al., 2015; Özkan et al., 2016). However, Tang et al. included only a graphic representation and did not supply impact values (Tang et al., 2019). Normalised impacts were calculated in this review by applying the respective normalisation factors to the characterisation impacts of Boenzi, Boenzi et al., Ferreira et al., Badioli et al. (Boenzi et al., 2019; Boenzi, 2022; Ferreira et al., 2015; Badioli et al., 2024). Detailed information on the normalisation process is provided in the supplementary material. Three articles couldn't be included in the analysis due to the lack of characterisation results (Canton et al., 2023) or the uncertain impact assessment method (Muñoz et al., 2020; Muñoz, 2023). Results interpretation assumes that higher normalised values refer to higher and more relevant environmental impacts. Marine ecotoxicity was found to be highly impacted in 70 % of the studies, while freshwater eutrophication, freshwater ecotoxicity and human toxicity were mentioned in about half of the assessed materials. Marine ecotoxicity recorded the highest normalised impact in twelve cases, making it the most significant impact category. Conversely, ozone depletion was the least impacted category in thirteen cases. Globally, negligible impacts are generated on ozone depletion in 90 % of the materials, followed by land use-related categories (65 %) and mineral resources depletion (35 %). Negative impacts, corresponding to environmental savings, were associated by Ferreira et al. with the closed-loop recycling of AZ bricks for marine, human and freshwater ecotoxicity (Ferreira et al., 2015). It is relevant to remember that the identification of critical impact categories could be influenced by biases inherent to the impact assessment methodology. For instance, many LCIA approaches question the robustness of

Table 4
Characterised results of the studies applying ReCiPe 2008 methodology. Selection of the most impacted environmental categories.

	MC	MS	MC	MA	AC	AZ disposal	AZ recycling	MZ disposal	MZ recycling
	(Boenzi, 2022) FU: 1t bricks production		(Boenzi et al., 2019) FU: 1t bricks production		(Tang et al., 2019) FU: 1t bricks production	(Ferreira et al., 2015) FU: 1t waste			
Marine ecotoxicity [kg 1.4-DCB-Eq]	27,46	15,36	28,16	10,26	40,73	8,06	−11,50	17,80	11,10
Freshwater eutrophication [kg P-Eq]	1,37	0,44	1,41	0,41	1,08	0,39	0,05	0,42	0,34
Human toxicity [kg 1.4-DCB-Eq]	960,79	429,76	985,37	352,45	1136,00	334,00	−82,90	647,00	427,00
Freshwater ecotoxicity [kg 1.4-DCB-Eq]	29,84	15,62	30,61	10,21	45,62	7,59	−11,20	18,90	11,30

characterisation mechanisms for toxicity categories, noting that they often lead to high uncertainties in toxicity impact results (European Commission, 2021; Dekker et al., 2020). However, despite uncertainty and variations in LCA set-up, methodologies and system boundaries, it appears that the highest and lowest categories in the criticality hierarchy are consistent across all analysed materials. Fig. 3 presents the normalised results of the studies applying the ReCiPe 2008 methodology, either in the main text or in the supplementary materials (Boenzi et al., 2019; Boenzi, 2022; Ferreira et al., 2015), except for Tang et al.'s work, which did not report the normalised values explicitly (Tang et al., 2019). As previously mentioned, for a matter of consistency, only values based on the same impact assessment method were compared. In the supplementary materials, the comparison of ReCiPe (2008) characterisation results is proposed to provide an indication of the impacts' order of magnitude.

Table 4 shows the characterised impacts calculated through ReCiPe 2008 by Tang et al., Boenzi et al., Boenzi and Ferreira et al. on the categories with the highest normalised results (Tang et al., 2019; Boenzi et al., 2019; Boenzi, 2022; Ferreira et al., 2015). While Ferreira et al. describe the management of end-of-life refractory waste (Ferreira et al., 2015), the other studies evaluate the production of refractory bricks (Tang et al., 2019; Boenzi et al., 2019; Boenzi, 2022). The table is meant to indicate the order of magnitude of refractories' environmental impacts. Further results interpretation is provided in the next section.

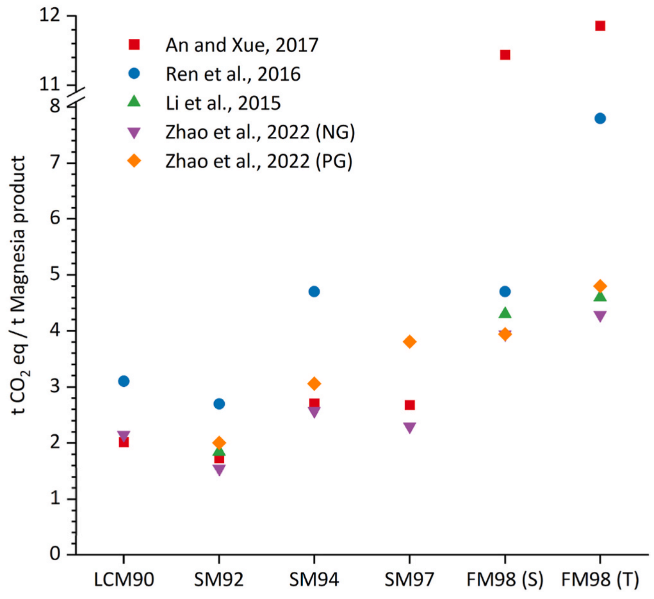

Fig. 4. CF of magnesia products. Nomenclature: "magnesia type - magnesia content (%)". (S) and (T) denote single- and two-step fused production, respectively. NG: natural gas, PG: producer gas.

5.4.2. *Identification of environmental hotspot and sensitivity analysis*

Hotspots are processes, materials and/or energy inputs that have a large contribution to the total environmental impact of a product. Sensitivity analysis supports hotspot identification by systematically determining which parameters significantly impact assessment results when changed. As climate change and greenhouse gas emissions are of primary relevance in the current environmental discussion, this section is mostly dedicated to their analysis.

5.4.2.1. GHG emissions. Fig. 4 summarises the GHG emissions associated with manufacturing various magnesia products (Ren et al., 2016; An and Xue, 2017; Zhao et al., 2022; Li et al., 2015). Considerable variation in the reported emissions is observed, despite all products originating from Chinese facilities. This variability can primarily be attributed to differences in manufacturing practices and the types of energy sources selected by the producers. Notably, An & Xue reported exceptionally high GHG emissions for FM relative to other studies (An and Xue, 2017); however, Zhao et al. subsequently indicated that this discrepancy results from calculation errors (Zhao et al., 2022).

Energy is observed to be the main contributor to GHG emissions of refractories and refractory raw materials in all studies. Specifically, the electricity mix is critical for fused products, while the source of heat is critical for sintered and calcined products. The key parameter driving energy impacts is the electricity mix in the first case, and fuel type and the energy intensity in the second. The emission factor attributed to energy sources strongly influences CF and LCA results. For instance, Ranaivoharilala et al. showed that producing white fused alumina in China has a CF over five times higher than in Austria (Ranaivoharilala et al., 2023). Indeed, while the Chinese electricity mix is mostly based on coal, the Austrian one relies on hydroelectric power, thus resulting in a way lower emission factor. However, primary data collected in Europe demonstrated that the energy demand for refractory production usually does not depend on the geographical location, but on operational parameters such as the kiln load (European Refractories Producers' Federation, 2013). In Ren et al., the manufacturing technology and industrial structure were mentioned as key factors to optimise energy efficiency and to adapt to the quality requirements asked by the refractory users (Ren et al., 2016). Several authors assessed the impact of the energy system in the form of sensitivity analysis. Li et al. considered scenarios for the electricity mix and supply of coal with a variation of the parameters of 1 % (Li et al., 2015). Muñoz et al. and Zhao et al. observed that the ongoing replacement of coal in favour of natural gas in the Chinese refractory industry could significantly improve the environmental performance (Muñoz et al., 2020; Zhao et al., 2022). However, some studies suggested that the treatment of off-gases could be a more efficient way of reducing GHG emissions, compared to the reduction of energy consumption. For instance, CO_2 capture and reuse solutions were proposed by An et al., Zhao et al. and Trojer to catch the unavoidable quota of geogenic emissions (An and Xue, 2017; Zhao et al., 2022; Trojer, 2009). Similarly, Özkan et al. concluded that waste gas treatment was more effective than improved energy efficiency in reducing the impacts of magnesia-spinel bricks production (Özkan et al., 2016). However, the implementation of additional treatments could increase the energy intensity (European Refractories Producers' Federation, 2013).

In refractory products, the energy consumption can be direct in the production process or indirect from producing raw materials. Hence, the refractory composition and the choice of raw materials can have a decisive impact on the environmental impacts associated with the final refractory product. For instance, Boenzi et al. demonstrated that the substitution of fused magnesia with sintered magnesia in the magnesia-carbon brick can significantly decrease the GHG emissions, together with other environmental burdens (Boenzi et al., 2019). This result can be explained by the lower emission factors of sintered magnesia described at the beginning of the chapter. Similarly, the magnesia-carbon brick showed higher impacts than the magnesia-alumina brick. The better environmental performance of the carbonless brick could be attributed to the lack of fused magnesia in the recipe, which is the main contributor to all the impact categories of magnesia-carbon brick. Different conclusions could be drawn when extending the system boundaries to the use phase (Boenzi, 2022). Indeed, due to its lower performance in use, the carbonless refractory globally generated equal or higher impacts than the magnesia-carbon one, indicating the material's performance as a key parameter. Yet, the author suggested interpreting the results carefully due to the low reliability of the forecasted operational parameters for the carbonless brick. A similar trend was observed for magnesia products by An et al. (2018). The higher emissions from FM production for large fused magnesia grains were offset by a longer service life, resulting in lower overall emissions during use. Yet, the author underlined the difficulty in estimating the service lifetime and the associated result variability. The opposite trend was shown in Henry-Lannier et al., where the consideration of the full application increased the difference in product carbon footprints (Henry-Lanier et al., 2016). However, the analysis didn't consider potentially influencing life stages such as transport and product installation. In conclusion, the literature shows that the carbon emissions of two materials meant for the same application differ less when considering the use phase.

5.4.2.2. LCA results. Approximately half of the environmental impacts from manufacturing refractory bricks are attributed to the production of their main raw material. Indeed, in Boenzi et al., fused magnesia and sintered magnesia generate more than half of the impacts for the MC and MA carbonless brick (Boenzi et al., 2019). This result is in line with Boenzi, despite some variations in the carbonless brick composition (Boenzi, 2022). In terms of absolute values, the magnesia-spinel carbonless brick shows lower impacts than MC, except for mineral resource use and human toxicity, which are negatively impacted by the production of alumina from bauxite (Table 4). The magnesia-spinel brick is modelled upon that proposed by Özkan et al., although the original study featured a somewhat different impact distribution (Özkan et al., 2016). Such variation was attributed partly to the raw materials production and partly to the energy consumption during drying and firing. Similarly, 45 % of the impacts are attributed to the production of sintered corundum in Tang et al. (2019). When considering larger system boundaries including the usage phase, as in Boenzi, the primary contribution comes from the energy consumption of the process using the refractories, such as heating molten steel in the ladle (Boenzi, 2022).

The results obtained in the LCAs assessing the end-of-life management scenarios were consistent with what is generally perceived on waste management. The results validated the hypothesis that refractory recycling could reduce environmental impacts by avoiding waste transport and disposal, as well as the production of raw materials. The reuse of magnesia-carbon bricks was proven even more environmentally advantageous than their recycling, due to the direct substitution of virgin bricks without previous treatments (Muñoz et al., 2020). Indeed, the low recycling rate and the energy-related burdens of the recycling activities limited the impact reduction from raw materials substitution (Muñoz et al., 2020). The environmental benefits reachable depend on many factors such as the waste refractory composition, the ratio of replacement of raw materials and the location of the recycling plant. In Ferreira et al., the highest benefit was obtained in the very same categories that were critical to the other materials and generally critical in literature (Table 4) (Ferreira et al., 2015).

5.4.3. Uncertainty analysis

Uncertainty is inherent in all phases of LCA, stemming from various sources such as measurement errors, data gaps, and methodological choices (Bamber et al., 2020). Despite the fact that uncertainty in data is considered one of the biggest limitations in environmental assessments, uncertainty analysis was not a common practice among the reviewed studies. Monte Carlo simulations have emerged as a prominent method for assessing uncertainty in LCA studies (Lam et al., 2020). Only two studies implemented Monte Carlo simulation at inventory level for both foreground and background systems with 95 % confidence interval. Muñoz's uncertainty analysis showed that the waste management scenario with recycling always leads to an environmental benefit compared to landfills for all impact categories within 2.5th to 97.5th percentiles (Muñoz et al., 2020). Quantitatively, LCA results varied within the uncertainty range but did not significantly change the study's qualitative conclusions. Tang et al. identified the background database as the primary contributor to uncertainty in the results (Tang et al., 2019). A different approach was followed by Joos-Bloch et al., who assigned a value between 1 (low) and 5 (high) to the uncertainty of each dataset used to calculate the product carbon footprint (Joos-Bloch et al., 2023). The findings indicated a significant correlation between high levels of uncertainty and the proportion of third-party raw materials. This underscores the importance of having access to supplier-specific data in ensuring the accuracy of the carbon footprint calculations. Neglecting uncertainty analysis in LCA studies can result in substantial misinterpretations of outcomes, leading to unreliable conclusions and poor decision-making. As highlighted by Bamber et al., omitting uncertainty considerations undermines the reliability and relevance of LCA findings, potentially driving stakeholders toward misguided environmental decisions (Bamber et al., 2020). Specifically, without thorough uncertainty evaluation, environmental impacts may be inaccurately represented, either exaggerated or minimised, thus influencing decision-makers to disregard genuinely sustainable solutions or adopt less optimal alternatives due to misplaced certainty. Given these implications, it is strongly recommended that uncertainty analyses be routinely incorporated into LCA studies concerning refractory products to enhance the robustness and credibility of the assessments.

6. Outlook and direction of future research

The review of current literature on the environmental performance of refractories provided many significant outcomes. The discussion presented here focuses on the life cycle assessment (LCA) method, which is preferred to the carbon footprint (CF) thanks to its global overview of the environmental performance over many impact categories. Based on the main methodological and data gaps described in Section 6.1, recommendations for future studies are drawn in Section 6.2. Three main topics are discussed: the scope of LCA studies, their methodological approach and data availability and quality.

6.1. Main findings and methodological gaps

The literature reported a variety of LCA methodological approaches. Each author developed an ad-hoc approach by adapting the scope of the study, the system boundaries and the impact assessment method to the product system of interest. As a consequence, the comparability of the results is impossible or rather questionable in terms of coherence and representativeness. Evidence of this inconsistency is found in the wide range of impact values calculated for the same product. For instance, the greenhouse gases emitted for producing magnesia-carbon bricks vary from 2 t CO2,eq/t bricks (Boenzi et al., 2019) to 10 t CO2,eq/t bricks (An et al., 2018). Results comparison is further complicated by inconsistent reporting practices, with compliance to ISO standards rarely achieved. Missing inventories, unspecified product composition and poor description of the methodological choices (e.g. avoided communication of the allocation approach) were the most common problems of non-ISO-compliant studies.

With respect to the systems described, existing LCA studies offer a limited description of the environmental performance of the refractory sector, particularly concerning the range of products, production methods, and geographic regions covered. The emphasis on raw material production was placed primarily on various forms of magnesia. Likewise, the LCAs of refractory manufacturing predominantly focused on magnesia-carbon and magnesia-spinel bricks. Therefore, a research gap has been identified in the evaluation of raw materials and refractories with acidic and neutral compositions, as well as in numerous manufacturing processes for both shaped and unshaped refractories. Also, most of the studies referred to European and Chinese production, resulting in a limited representation of worldwide patterns. Lastly, the usage and end-of-life management of refractories were only represented in a limited number of cases, as mentioned in 5.1.1.

The low representativeness of existing products was generally accompanied by the low geographical, technological and time coverage of available inventories. Only a few studies provided complete inventories based on primary data, most related to Chinese manufacturing practices. In the case of European refractory manufacturers, data confidentiality and competitiveness most often prevented data sharing. Hence, Chinese data were used as a proxy for product systems in other countries, which limited the representativeness of the related LCA results. At present, most of the inventories in the literature are considered outdated, as these were collected more than 10 years ago. Their representativeness in terms of time and technology is constrained by the omission of recent technological developments. For instance, the strict legislation imposed by Chinese authorities since 2018 to promote sustainability in the magnesia industry has significantly improved energy efficiency, cleanliness and reduced direct or indirect CO2 emissions (Zhao et al., 2022).

Despite these differences and limitations, common trends were identified in the environmental performance of refractory raw materials and products. As described in Section 5.4.2, energy supply, whether as electricity or fuel, is the main driver of GHG emissions arising from raw materials production. The LCA studies on refractory bricks manufacturing attribute approximately half of the environmental impacts to raw materials supply and around 40–50 % to energy supply. The relative significance of marine ecotoxicity, freshwater eutrophication, freshwater ecotoxicity and human toxicity is observed to be higher than the other impact categories (Tang et al., 2019; Boenzi et al., 2019; Boenzi, 2022; Ferreira et al., 2015; Özkan et al., 2016; Badioli et al., 2024). However, the uncertainty surrounding toxicity characterisation models makes the results questionable and requires further investigation in future research. The literature reveals no consistent correlation between the technical and environmental performance of refractories, largely due to the difficulty in defining or comparing technical properties across materials and products. In the case of magnesia forms, fused magnesia typically exhibits superior technical properties compared to sintered magnesia and shows higher CO_2-equivalent emissions, if fossil-based electricity is utilised in the fusion process (Ren et al., 2016; Zhao et al., 2022). However, sensitivity analyses in various studies suggest that changes in the energy mix could significantly alter GHG emissions for both sintered and fused magnesia, potentially overturning such findings (Muñoz et al., 2020; Zhao et al., 2022; Ranaivoharilala et al., 2023; Li et al., 2015). In the context of refractories, a comparison by Boenzi et al. of two bricks designed for the same application illustrates the challenges of evaluating the technical and environmental performance of these products in complex operational settings (Boenzi, 2022). Uncertainties in the parameters used to simulate working conditions limit the representativeness of the results, which indicate comparable technical and environmental performance. Moreover, such outcomes are heavily influenced by the LCA methodology, particularly the selection of functional units and system boundaries.

6.2. Recommendations for future research

The key recommendations for future research outlined in this review can be summarised as the need to broaden the scope of studies on the environmental performance of refractories and to develop a standardised methodological approach.

The scope expansion refers, first of all, to promoting LCA over CF, for a thorough assessment of all impact categories and the avoidance of burden shifting. Secondly, the limited LCA literature on refractories highlights the need to cover unexplored products and production routes in future research. Such an effort would guarantee a global representation of the refractory industry and provide deeper insight into its environmental performance. Particular attention should be given to new production routes involving the use of recovered materials, lower quality resources and clean energy. Also, the inventories of products already studied in the literature should be updated in terms of mainstream technologies and energy sources. In parallel, a better geographical coverage should be favoured by modelling materials processing and use in more countries than those already addressed.

Thirdly, the expansion of the system boundaries towards the full life cycle in a cradle-to-grave or cradle-to-cradle approach is suggested. Indeed, the literature showed that including the use phase can reverse LCA results when comparing materials for the same application (Boenzi, 2022). In other words, the material performance appeared to be as relevant as the production burdens when assessing its environmental performance.

Since inventory data form the foundation of LCA, alongside scope expansion, efforts must be made to collect primary data to compile high-quality inventories that ensure representative and reliable assessments. Some authors attributed the problem of data availability and quality to the lack of engagement of stakeholders (Joos-Bloch et al., 2023; Menezes Cunha et al., 2023). LCA-based regulations and consequent economic measures could be effective tools for motivating, or forcing, stakeholders to perform LCA and collect the necessary primary data (Menezes Cunha et al., 2023). The term stakeholder refers to all the companies and actors involved in the refractories' supply chain. Indeed, data gaps were found especially in upstream mining activities and raw materials supply, as well as in downstream refractory usage and end-of-life. Data sharing within a network of stakeholders could effectively address the current obstacle to performing cradle-to-grave LCAs, caused by refractory manufacturers' limited ability to predict the use phase and end of life of their products (Mottram et al., 2023). Therefore, data collection and sharing could be supported by proposing large-scale initiatives, such as the one promoted by the European Refractories Producers Federation (PRE), who already published the gate-to-gate carbon footprint of five refractory product groups (European Refractories Producers' Federation, 2013). The World Refractory Association (WRA) may take a similar initiative, collecting data from its members and periodically publishing updated assessments of refractories. Detailed information on production processes and related inventories is provided, and regularly updated, by the Joint Research Centre in the Best Available Techniques Reference Document for the Ceramic Manufacturing Industry (European Commission, 2007). The publication could be considered a reference for presenting inventory data. The multi-regional approach of data collection and LCA would facilitate inter-regional comparison and benchmarking products or groups of products at regional level (Lam et al., 2020). Uncertainty and sensitivity analyses should be prioritised in LCA studies to account for data uncertainty.

In addition to improving primary data availability, future efforts should focus on enhancing the quality of measured data. Most current measurements are conducted at the plant level or represent averages across facilities located in different countries. In-house average data are often adapted to various products by allocating energy and material flows based on experts' judgment. This practice introduces biases that prevent depicting the real environmental performance of the products. Hence, stakeholders should ameliorate the monitoring and measurement systems in place to collect new process-level, product-specific, reliable and representative data. In parallel, LCA practitioners should use the latest versions of commercial databases, referring to up-to-date background data, in their assessments.

Regarding LCA methodology, the challenges and inconsistencies reported in this review highlight the need for guidelines to favour standardisation and enhance the methodological practice. Hence, refractory manufacturers and the LCA community should collaborate to develop dedicated product category rules. Specific attention should be paid to the allocation approach and end-of-life modelling, as the zero-burden assumption applied to refractory waste recycling has been questioned by many researchers (Lam et al., 2020; Pradel et al., 2016). In parallel, further research is needed to identify the most suitable impact assessment method. Although this review does not investigate the topic, the environmental footprint method (EF 3.1) proposed by the European Commission appears to be a suitable option, as it serves as the reference model in Europe (European Commission, 2021). Regardless of the choice, the literature highlights the absence of characterisation factors for key raw materials such as magnesite and bauxite (Li et al., 2015). Alongside ongoing debates concerning the methodology for calculating resource depletion factors, this raises concerns about the reliability of resource depletion assessments (Menezes Cunha et al., 2023). Additionally, it is proposed to align with the Product Environmental Footprint (PEF) recommendations for results interpretation, by selecting meaningful impact categories at ponderation stage instead of normalisation (European Commission, 2021). This approach would better reflect the robustness of characterisation methods and help reduce uncertainties in the interpretation of results.

Aside from the methodology set-up, future studies should be more rigorous in the communication of LCA results, with specific attention to declaring inventories and making them accessible to the public.

7. Conclusions

Out of the twenty-one reviewed studies, ten applied the LCA methodology, while the others focused on the carbon footprint or GHG emissions of refractories and refractory raw materials. The studies referred to a narrow range of products, mainly investigating magnesia-based materials intended for the steelmaking industry. Most assessments focused primarily on production, with limited attention given to the use and end-of-life stages, despite their substantial contribution to the overall environmental burdens. The variability in methodological choices across studies regarding goal and scope definition, functional unit, and impact assessment method created challenges for comparability and consistency in LCA results. The different system boundaries, coupled with the limited availability of primary data and the reliance on stoichiometric calculations and generic databases, introduced inconsistencies and uncertainty at the inventory level. Omitting uncertainty analysis and data collection context limits robust conclusions on the environmental impact of refractory materials. Although different LCA setups made direct material comparisons difficult, energy consumption was identified as the main environmental concern in most cases. In addition, many studies considered potential improvement scenarios by changing the energy mix and efficiency.

The challenges highlighted in this review suggest that several significant issues need to be addressed in future research:

- Development of methodological guidelines to improve the LCA practice, as harmonisation is key to comparability, representativeness and reliability of results. The proposition of a category rule is suggested.
- Improvement of generic and specific databases, by both updating old datasets and creating new ones.
- Expansion of stakeholder network for data collection, including upstream raw materials' suppliers and downstream refractories' users. This would allow a significant decrease in uncertainties and the need for secondary data.
- Transition from carbon footprint to life cycle assessment to be favoured at the company level, to perform global environmental analyses and avoid trade-off among environmental domains.
- Expansion of the system boundaries to include all life cycle steps in cradle-to-cradle LCAs, with special attention to the inclusion of upstream raw materials processing and downstream usage of refractory products.
- New LCA studies covering current gaps in terms of refractory products, new technologies and geographical areas.

Ultimately, this review emphasises the need for harmonized LCA methodology, improved data quality, and broader life cycle perspectives to drive meaningful and measurable environmental progress within the refractory materials industry.

CRediT authorship contribution statement

Sarah Badioli: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Md Jubayed:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Marielle Dargaud:** Writing – review & editing. **Rinus Siebring:** Validation, Supervision. **Angélique Léonard:** Writing – review & editing, Validation, Supervision.

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.

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Appendix A. Supplementary data

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Data availability

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

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