Supplementary material

Nomenclature			
AC	Alumina Carbon	M	Magnesia
AZ	Alumina Zirconia	MC	Magnesia Carbon
CA	Calcined alumina	MS	Magnesia Spinel
FM	Fused Magnesia	MZ	Magnesia Zirconia
LCM	Light Calcined Magnesia	WFA	White Fused Alumina
CF	Carbon Footprint	LCA	Life Cycle Assessment

Literature selection

The present literature review article analyses twenty-one studies describing the environmental profile of refractory materials through carbon footprint and life cycle assessment. Figure S1 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 timeframe boundary for the selection of literature, no studies were found for the period 2009-2011.

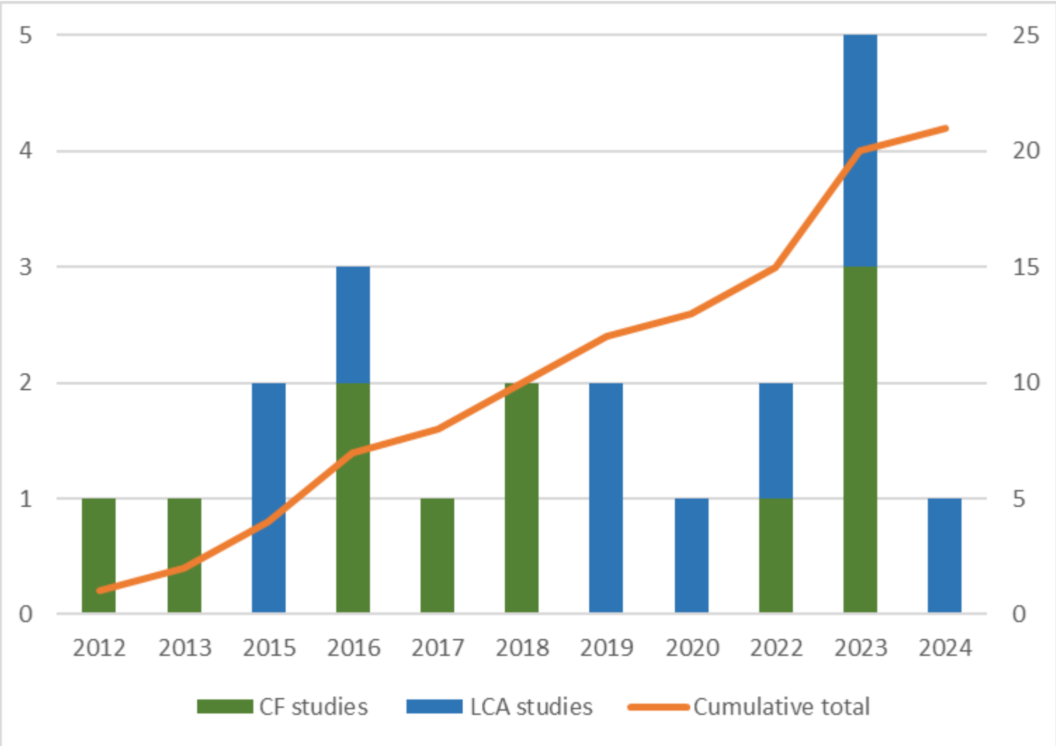

Figure S1 Distribution of LCA and CF studies per year of publication

LCA results interpretation: Identification of critical environmental domains

The analysis of the normalised LCA results allows the identification of critical environmental impact categories..

Table S1 describes the characteristics of the selected LCA studies for which the normalisation was possible. First, either normalised results were provided in the literature, or the authors applied the normalisation factors to the characterisation results of the assessed studies. Second, every impact assessment methodology provides its own interpretation of the environmental classes and impacts, hence the LCIA method is mentioned. In addition, the version of the methodology is provided, to take into account the eventual update of the normalisation factors. Lastly, a context for the LCA is provided in terms of analysed product, system boundaries, timeframe and location.

Table S1 Description of the LCA studies assessed for the identification of the critical environmental domains

Reference	year	Product	Boundaries	Functional Unit	LCIA method	Geography	Normalised results provided
Tang et al. [2]	2019	AC brick	RM, REF	1 t product	ReCiPe H 2008	China	Yes
Li et al. [51]	2015	LCM, FM	RM	1 t product	CML 2001-Nov.2010	China	Yes
Özkan et al. [52]	2016	MS brick	RM, REF	1 t product	CML-IA baseline v.3	Europe	Yes
Boenzi [28]	2022	MC, MS bricks	RM, REF, U	1 t steel produced	ReCiPe H 2016 (v1.1)	Europe	No
Boenzi et al. [36]	2019	MC, M bricks	RM, REF	1 t product	ReCiPe H 2008 (v1.11)	Europe	No
Ferreira et al. [50]	2015	AZ, MZ	EOL	1 kg waste management	ReCiPe H 2008	Europe	No
Badioli et al. [54]	2024	LCM, CA, FM, WFA	RM	1 t product	EF3.1	China	No

The normalisation of LCA results allows to represent all the environmental impacts with the same unit, i.e. "person equivalent", hence making them comparable. A criticality hierarchy can be defined, where the impact categories showing the highest normalised values are the most impacted by the product, thus the most critical. On the contrary, lower impact values are associated with lower criticality. In this study, the three highest and lowest impacts of each products are selected. Table S2 describes the analysis of the most critical impacts, and Table S3 describes the least critical ones. In order to represent the hierarchy of the impacts, values from 1 to 3 are attributed to the selected impacts, where 3 refers to the higher value and 1 to the lower value. Given the variety of impact assessment (IA) methods used in the analysed articles, a generalisation of the impact categories was applied in order to group similar categories. This is the case of human toxicity, that in some IA methods is represented by two categories named cancer and non-cancer. Similarly, under the term land use are considered all the categories associated with land use, occupation and transformation. The effect of the IA methodology on the LCA results is clearly visible in Boenzi [28], who performed the LCA through both ReCiPe 2008 and ReCiPe 2016 methodology. The two methods describe environmental impacts through different categories, hence the criticality hierarchy of the same product in the two versions could vary. For example, ReCiPe 2008 considers the classes natural land transformation and agricultural land occupation, that are not available in ReCiPe 2006. Vice versa, the 2016 method considers two sub-categories for human toxicity, cancer and non-cancer, and introduces a normalisation factor for water use.

The normalised results highlight trends for the refractory materials. Table S3 describes the least impacted categories. Neglectable impacts were generated on ozone depletion in 90% of the study, on land use (65%), and mineral resources depletion (35%). In more than half of the studies, ozone depletion register the lowest impact value. Table S2 Table S3 describes the least impacted categories. Neglectable impacts were generated on ozone depletion in 90% of the study, on land use (65%), and mineral resources depletion (35%). In more than half of the studies, ozone depletion register the lowest impact value.

Table S2 Analysis of normalised results of selected studies: definition of the most critical categories. The highest impact is assigned a value of 3, the second highest is assigned 2, and the third highest is given a value of 1.reveals that marine ecotoxicity was critical in 70% of the studies, while freshwater eutrophication, freshwater ecotoxicity and human toxicity were mentioned in about half of the studies. Also, marine ecotoxicity registered the highest normalised impact in twelve cases. Table S3 describes the least impacted categories. Neglectable impacts were generated on ozone depletion in 90% of the study, on land use (65%), and mineral resources depletion (35%). In more than half of the studies, ozone depletion register the lowest impact value.

Table S2 Analysis of normalised results of selected studies: definition of the most critical categories. The highest impact is assigned a value of 3, the second highest is assigned 2, and the third highest is given a value of 1.

Reference	Material	Freshwater ecotoxicity	Freshwater eutrophication	Human toxicity	Marine ecotoxicity	Acidification	Global Warming Potential	Fossils resource depletion	Particulate matter formation
[2]	AC brick	2	1		3				
[51]	1-step FM			2	3		1		
	2-step FM			2	3	1			
	2-step FM recycling scenario			2	3		1		
	1-step FM, improved scenario			2	3	1			
[52]	MS brick				3	2	1		
[28]	MC brick (ReCiPe 2016)	1	2	3					
	C-less brick (ReCiPe 2016)		2	3	1				
	MC brick (ReCiPe2008)	2	1		3				
	C-less brick (ReCiPe2008)	2	1		3				
[36]	MC brick	2	1		3				
	C-less brick	2	1		3				
[50]	AZ disposal	1		2	3				
	AZ recycling		3					2	1
	MZ disposal	1		2	3				
	MZ recycling	1		2	3				
[54]	LCM		1				3		2
	CA		2	4[a]					
	2FM						1	2	3
	WFA		1	3				3	
N° studies (n)		9	11	11	14	3	5	3	3
N° studies (%)		45%	55%	55%	70%	15%	25%	15%	15%

[a] Human toxicity appears as critical twice as cancer (1) and non-cancer (3) toxicity

Table S3 Analysis of normalised results of selected studies: definition of the least impacted categories. The lowest impact is assigned a value of 1, the second lowest is assigned 2, and the third lowest is given a value of 3.

Reference	Material	Land use	Marine eutrophication	Mineral resource depletion	Ozone depletion	Terrestrial ecotoxicity	Freshwater ecotoxicity	Ionising radiation	Marine ecotoxicity	Human ecotoxicity
[2]	AC brick				1	2		3		
[51]	1-step FM			2	1		3			
	2-step FM			2	1		3			
	2-step FM recycling scenario			2	1		3			
	1-step FM, improved scenario			2	1		3			
[52]	MS brick			1	2	3				
[28]	MC brick (ReCiPe 2016)	2		1	3					
	C-less brick (ReCiPe 2016)	2	3	1						
	MC brick (ReCiPe 2008)	5[a]			1					
	C-less brick (ReCiPe 2008)	2			1	3				
[36]	MC brick	5[a]			1					
	C-less brick	2			1	3				
[50]	AZ disposal	1			2	3				
	AZ recycling						2		3	1
	MZ disposal	4[b]			2					
	MZ recycling	4[b]			2					
[54]	LCM	3			1			2		
	CA	3			1			2		
	2FM	3			1			2		
	WFA	3			1			2		
N° studies (n)		13	1	7	18	5	5	5	1	1
N° studies (%)		65%	5%	35%	90%	25%	25%	25%	5%	5%

[a] The general "land use" category represents natural land transformation (3) and agricultural land occupation (2)
[b] The general "land use" category represents urban land occupation (3) and agricultural land occupation (1)

Besides the evaluation of normalised results, Table S4 compares the characterisation results of the sources [2,28,35,49] for the most and least impacted categories to provide an indication of the impacts' order of magnitude. The studies were chosen as they apply the same impact assessment methodology, namely ReCiPe 2008, as either in the article or in the supplementary materials. Data from [2,28,35] describe the production of refractory brick, while [49] refers to the end of life management of refractory waste.

Table S4 Characterisation results of the LCA studies applying ReCiPe 2008 methodology. Selection of most and least impacted environmental categories

	MC	**MS**	**MC**	**MA**	**AC**	**AZ disposal**	**AZ recycling**	**MZ disposal**	**MZ recycling**
	[28] FU: 1t bricks		[35] FU: 1t bricks		[2] FU: 1t bricks	[49] 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
Ozone depletion [kg CFC-11-Eq]	1,20E-04	1,52E-04	1,23E-04	1,27E-04	1,98E-04	1,39E-04	4,85E-05	1,93E-04	1,84E-04
Agricultural land occupation [m2a]	72,42	12,72	74,27	11,63	166,70	15,00	9,62	15,00	13,40
Urban land occupation [m2a]	16,61	15,83	17,03	14,18	28,92	20,60	5,05	12,90	10,50
Natural land transformation [m2]	0,26	0,30	0,26	0,27	0,31	0,32	0,23	0,47	0,47
Metal depletion [kg Fe-Eq]	25,66	21,48	26,31	15,38	188,50	65,00	26,30	937,00	934,00