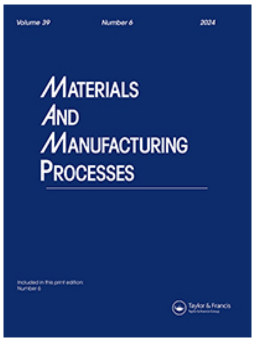

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Steel slag as a low-impact filler in rubber compounds for environmental sustainability

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ABSTRACT
This study investigates the use of electric arc furnace (EAF) slag, as a substitute for conventional filler, such as calcium carbonate, in nitrile-butadiene rubber (NBR) composites in different volume fraction. The results demonstrate that slag exhibits morphological traits comparable to calcium carbonate when used as a filler, moreover their processability and mechanical properties are similar. Specifically, at 20% v/v, slag-filled NBR exhibits slightly longer scorch times but unchanged vulcanization times. Both fillers at 20% v/v show comparable hardness, compression strength, and elastic modulus. Tensile properties are also comparable, except for the strain at break, where slag-filled NBR shows a 40% higher tensile strain at break. The environmental impact of this innovative slag application has been evaluated through a comparative life cycle assessment. All assessed impact categories demonstrate a reduction of at least 89%. The study suggests that the use of EAF slag has the potential to promote sustainable waste management.

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KEYWORDS
EAF slag; filled nitrile-butadiene rubber; industrial symbiosis; life cycle assessment

Introduction

Resource conservation and materials recycling play a crucial role in ensuring the sustainable use of natural resources, maintaining their availability for future generations, and reducing environmental impact.[1,2] The present study aims to prevent the landfilling of the main steel waste, i.e., the electric arc furnace (EAF) slag assessing its potential as a substitute of a conventional low-cost filler, i.e. calcium carbonate, in nitrile-butadiene rubber (NBR) applications. Exploring innovative reuse applications for this industrial waste aligns with circular economy goals of material efficiency and sustainability. By investigating EAF slag as a substitute for conventional fillers in rubber composites, this study provides both a quantitative life cycle assessment highlighting significant environmental benefits of this alternative and experimental results on the new compounds' performances. The comprehensively analyzed approach exemplifies industrial symbiosis that tackles the problem of slag landfilling while reducing reliance on virgin mineral extraction. Thereby this work filled the knowledge gap around slag's feasibility and footprint reduction potential as an alternative filler, guiding future materials selection and management decisions toward more sustainable practices.

In 2022, Italy has produced almost 20 Mt of steel through the EAF process,[3] and since the majority of producers are in located in Lombardy. It is estimated that in this region alone, the production of EAF slag reached about 1.3 Mt in the same year.[4] Over the last decades, an increasing number of studies have deepened the slag characterization to promote its reuse and mitigate the escalating costs and environmental impacts associated with landfilling.[5–8] Literature studies highlight the successful integration of also other steel industry wastes, particularly Linz – Donawitz (LD) sludge and slag, into polymeric matrices.[9–13] These studies reveal substantial improvements in the physical, mechanical, and erosion wear properties of resulting composites. For instance, incorporation of LD sludge enhances compressive strength and hardness in polypropylene matrices, while LD slag contributes to increased density, hardness, and compressive strength in epoxy composites. These findings underscore the promising potential of steel industry waste as a valuable and effective filler material, offering enhanced properties for polymeric composites in various applications. As regards EAF slag, due to its chemical-physical similarities to volcanic rock,[14] it is widely used both as a by-product and as an end-of-waste in the construction industry as an artificial aggregate.[5,15,16] However, it is estimated that about 8%, equivalent to 100.000 tons of EAF slag, is still disposed of in landfills in Lombardy,[4] hence exploring new applications to further reduce landfill disposal is mandatory.

In this context, EAF slag has been evaluated as a non-traditional filler material in various polymeric matrices.[17–23] The EAF slag has been compared to a low-cost, conventional filler, such as calcium carbonate, under identical conditions (including the same NBR matrix, filler volume fraction, and granulometry). Calcium carbonate, commonly employed as a cost-saving extender in rubber composites, provides economic benefits by reducing the requirement for more expensive polymers.[24] The production of EAF slag entails an environmental footprint, including CO_2 emissions and resource utilization. Therefore, it is advisable to promote sustainable practices to minimize these impacts. The environmental impact of using EAF slag as filler in rubber composites provides a quantitative sustainability comparison with calcium carbonate. The outcomes of this analysis will guide material selection considering factors such as performance,

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cost, and environmental considerations. In this study a comparative analysis was carried out between EAF slag and calcium carbonate as fillers, assessing their chemical-physical and morphological characteristics. Afterward, the influence of both fillers on the NBR matrix was evaluated at equal percentages by volume (0, 5, 10, and 20% v/v) in terms of processability and mechanical properties. To provide a more thorough analysis of this application, an environmental impact assessment of the material filled at 20% v/v was also performed through a comparative life cycle assessment (LCA). This assessment aim to provide insights into the sustainability benefits and tradeoffs associated with using EAF slag as an alternative to conventional calcium carbonate filler in NBR composites at equal performance.

Materials and methods

Materials

A Nitrile Butadiene Rubber (NBR) with a nominal hardness of 70 Shore A (carbon black 40 phr, vulcanized with sulfur) supplied by Novotema Spa (Italy) was used as a matrix. An EAF slag obtained from carbon steel production has undergone grinding and sieving (<100 µm) for investigating its potential as filler. A commercially available calcium carbonate ($CaCO_3$) with an equivalent particle size was used as a conventional inert filler reference.

The study aims to compare the impact of using slag as a replacement for calcium carbonate, at an equal volume percentage. This decision was based on the fact that the evaluation of the effect of fillers on composites is usually evaluated in terms of volume percent, as they have a significant influence on the properties of the composite. The utilization of identical weight percentages was avoided due to the inherent density disparity between calcium carbonate and slag (2.7 g/cm^3 and 3.7 g/cm^3 respectively), which could introduce extraneous variables. The density of calcium carbonate was provided in the material datasheet, while the density of EAF slag was determined through Archimedes' method according to the standard ASTM D792[25] on unpulverized slag samples (approximately 0.5–1 g). The specific tested compounds are listed in Table 1.

The composites were fabricated via calendering process to disperse the filler particles within the uncured NBR matrix. Subsequently, test sheets with thickness of 2 mm and 6 mm were obtained through compression molding. The vulcanization process was carried out for 5 and 10 minutes, respectively, at a temperature of 170°C. The samples for the mechanical tests are obtained by mechanical punching.

Table 1. EAF slag and $CaCO_3$ percentage by weight with the equivalent percentage by volume.

Filler	EAF Slag	$CaCO_3$
[%v/v]	[%wt.]	[%wt.]
0	0	0
5	13,6	10,3
10	24,9	19,5
20	42,7	35,3

Methods

Filler characterization

EAF slag chemical composition was determined by X-ray fluorescence spectroscopy and its leaching behavior was assessed following the standard CEN EN 12,457–2.[26] Standard test parameters were followed, except for the slag grain size, which was tested at <100 µm instead of the typical 4 mm size. The granulometric curve was used to investigate the grain size distribution. Stacked sieves with progressively smaller mesh sizes (100, 90, 63, 45, 32 µm) were used in the test to pass the filler through the stacked sieve tower. The particles were retained in different sieves, resulting in the distribution of filler particles. This deviation was made considering the influence of granulometry on leaching behavior.[19,21,23] The eluates obtained were then analyzed using an Optical Emission Spectrometer to measure the concentrations of Cr, Mo, and V, with three measurements taken for each. Additionally, the morphology of the particles was investigated through SEM observation of gold-coated powders. Furthermore, the chemical composition of the filler particles in EAF slag and $CaCO_3$ was determined using SEM with EDXS.[27] The analysis focused on small filler areas in BSE mode to provide detailed insights into the composition of the filler materials.

Compound characterization

Rheometric parameters were obtained under specific conditions, including a plate temperature of 177°C, 0.5 degrees oscillating force, and a 5-minute testing period according to the ASTM D5289 standard.[28]

The compounds' hardness was measured according to Shore A (SHA) hardness and micro International Rubber Hardness Grade (mIRHD) following the ASTM D2240[29] and ASTM D1415[30]standard on rectangular test plates of thickness 6 mm and 2 mm, respectively. The compression test was performed according to the ASTM D575[31] standard, employing a strain rate of 10 mm/min on cylindrical specimens measuring 12 × 6 mm. The compression set was determined according to theASTM 395 (method b) standard[32] on cylindrical specimens measuring 12 × 6 mm. Tensile tests were performed according to the ASTM D412 standard[33] on dumb-bell with length if gauge section of 25 mm and section 4 × 2 mm. It is noteworthy that all mechanical tests were performed on a minimum of 3 samples for each compound to ensure reliability and consistency of results.

Life cycle assessment (LCA)

Goal and scope. The primary objective of this study is to assess and compare the environmental impact associated with the production of NBR filled with EAF slag and NBR filled with $CaCO_3$ at an equal filler volume fraction.

The investigation is particularly relevant due to the substantial quantity of EAF slag generated in northern Italy, prompting exploration into innovative applications of this waste material and its corresponding environmental implications.

Employing LCA methodology to evaluate the environmental performance of NBR compounds can assist rubber compounders in minimizing the environmental footprint of fillers, thereby contributing to the development of more sustainable product. On the other side the valorization of the EAF slag, the main steelmakers waste, could potentially result in cost savings associated with waste disposal, leading to economic benefits.

The study considers system boundaries from cradle to gate level for the manufacture of 1 dm^3 of NBR compound filled at 20%v/v, which is the functional unit adopted. Two distinct scenarios are examined (see Fig. 1):

Scenario1: production of 1 dm^3 of $CaCO_3$ filled NBR, following the phases reported in the red box, while simultaneously landfilling EAF slag.

Scenario 2: production of 1 dm^3 of EAF slag filled NBR, following the phases outlined in the red box (Fig. 1), with the concurrent avoidance of $CaCO_3$ production.

Both scenarios are further subdivided into components production, transport, and manufacturing stages. The study adopts a comparative approach, assuming an equal quantity of NBR (as matrix) for both scenarios, thereby excluding its production from the boundaries of the system analyzed. Similarly, environmental loads associated with the slag production process have not been considered, as it represents an inevitable waste of steel production. These neglected process units are denoted in gray in Fig. 1. The study aims to provide insights into the environmental implications of these scenarios, guiding decisions toward more sustainable and economically beneficial practices.

Inventory analysis

The inventory analysis utilized primary data from laboratory experiments on the recipes of NBR with fillers, and secondary data mainly from the Ecoinvent 3.9 database on $CaCO_3$ production, transport, slag disposal, and electricity production. The allocation rules used in the "Ecoinvent 3 - allocation, cutoff by classification" database were maintained for secondary inventory data.

The weight of each filler in the functional unit varies, and the details are provided in Table 2. In scenario standard S1, which represents the standard case, the production of one functional unit requires the use of 542 g of $CaCO_3$. Simultaneously, 740 g of EAF slag is generated and subsequently landfilled. In the innovative scenario 2 (S2), the production of one functional unit also requires 740 g of EAF slag. However, in this scenario, the EAF slag serves as a filler, eliminating the need for $CaCO_3$. This innovative

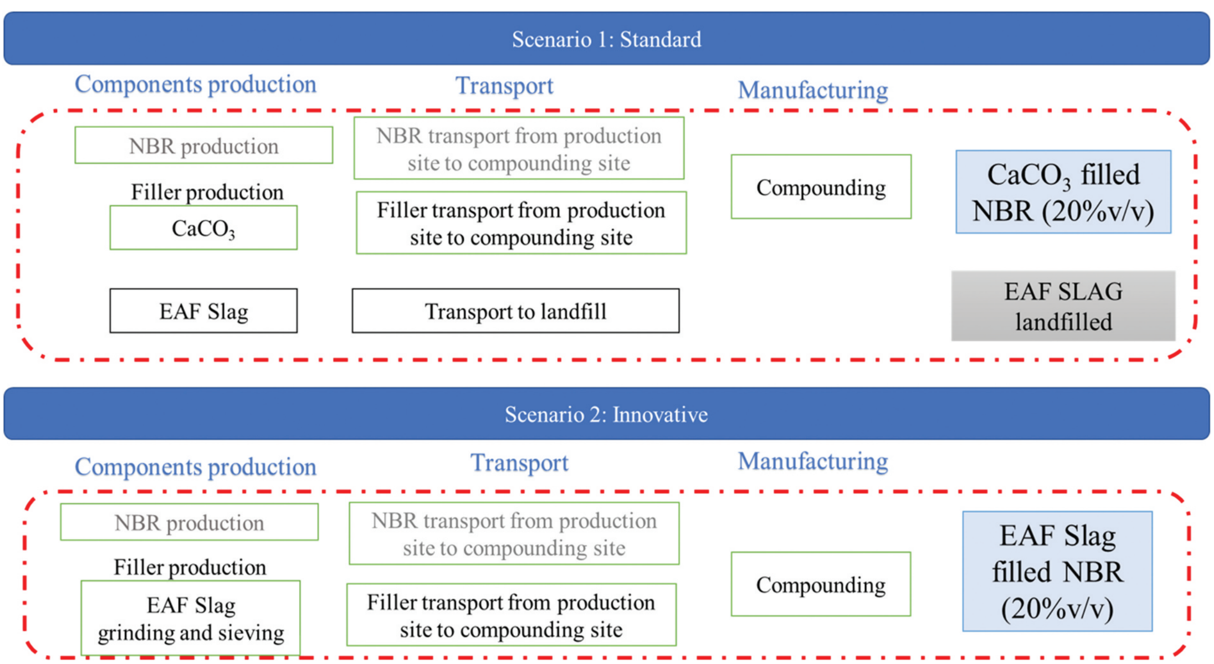


Figure 1. Diagram flow and boundaries of the production of 1 dm^3 of $CaCO_3$ filled NBR at 20%v/v (scenario 1) and EAF slag filled NBR (scenario 2). The process units written in gray have not been quantified as they are common to the two scenarios.

Table 2. Quantity of materials needed for producing 1 dm^3 of NBR filled at 20%v/v. *in S1 scenario standard 740 g of EAF slag is landfilled.

Scenario	Filler 20% [v/v] $CaCO_3$ (Density 2,7 g/cm^3)	Filler 20% [v/v] EAF Slag (Density 3, 7 g/cm^3)	Matrix 80% [v/v] NBR	Composite
	[g]	[g]	[g]	[kg]
S1 Standard	542	*740**	992	1,534
S2 Innovative	0	740	992	1,732

approach contributes to the recycling of waste material, aligning with sustainable practices and reducing dependency on virgin resources. The comparison between the two scenarios highlights the shift from conventional practices in Scenario 1 to an innovative and more environmentally friendly approach in Scenario 2. The use of EAF slag as a filler not only addresses waste management concerns but also reduces reliance on traditional fillers like $CaCO_3$, thereby showcasing potential environmental benefits.

In scenario standard S1 the environmental impact associated with the components production, namely calcium carbonate and the management of EAF slag for disposal, is assessed. The inventory data for calcium carbonate production is sourced from the Ecoinvent database, specifically under the entry *Calcium carbonate, precipitated {RER}| market for calcium carbonate, precipitated | Cut-off, U.*[34] The environmental load related to EAF slag management for disposal is also obtained from the Ecoinvent database, utilizing the entry *Electric arc furnace secondary metallurgy slag, for recovery {GLO}| electric arc furnace secondary metallurgy slag, for recovery, Recycled Content cut-off | Cut-off, U).*[34]

The database entry for chemical compounds production integrates data on the production of various chemicals involved in the process. The information is sourced from industry and literature. This entry also includes details on resource consumption such as heat, electricity, water, nitrogen, and other relevant resources.[34]

In scenario Innovative S2, where EAF slag is used as filler, a grinding process is employed to reduce the slag to a size suitable for this application, i.e., less than 0.1 mm. This grinding process necessitates additional energy consumption, estimated at around 25–35 watt-hours based on data provided by a steel mill. For the purpose of a worst-case scenario analysis, the energy consumption attributed to the slag processing is assumed to be 35 kilowatt-hours. This approach of utilizing EAF slag as a filler in Scenario 2 reflects an innovative and sustainable practice, although it introduces an additional energy cost for the grinding process. This comprehensive assessment aims to provide a holistic understanding of the overall environmental implications of the new approach. Furthermore, the study considers the transport of both filler from the production site to the treatment site and, as last, to the building site for application. The transport distance is assumed to be 100 km, and the mode of transport is a Euro 5 lorry with a capacity of 16–32 metric tons. The inventory data for transport is sourced from the Ecoinvent database under the entry "*Transport, freight, lorry 16–32 metric ton, EURO5 {RER}| transport, freight, lorry 16–32 metric ton, EURO5 | Cut-off, U*".[34]

By accounting for the transportation impact, the study enhances its environmental assessment, recognizing the significance of logistics in the life cycle of the materials. This approach ensures that the overall environmental footprint of the innovative practice, from filler production to application, is comprehensively addressed and considered in the decision-making process.

In scenario standard S1, the disposal of EAF slag involves landfill, as per the Ecoinvent entry "*Ecoinvent Electric arc furnace slag {RoW}| treatment of electric arc furnace slag, residual material landfill | Cut-off, U.* Historically, by-products of steel production, such as slag, dust, and sludge, were commonly disposed of in landfills. However, due to evolving regulations and landfill taxes, this practice is declining. Efforts are underway to reuse or sell these byproducts. The steel industry is increasingly focusing on finding alternative uses, recycling, or selling these by-products. While the proportion of these by-products sent to landfills has decreased, residual material landfills may still receive some of them. The landfilling process involves waste reception, leading to emissions, including leachate and groundwater contamination. Specifically, in the case of Electric arc furnace slag landfilling, there is a solidification stage that requires the use of 0.4 kg of cement per 1 kg of slag. This solidification process aims to render the material inert, reducing its potential environmental impact.

It's worth noting that the disposal of industrial by-products in landfills is associated with environmental challenges and efforts to minimize such practices align with sustainability goals, emphasizing the need for innovative and environmentally friendly solutions, as explored in Scenario 2.

Impact assessment

The environmental impact assessment in this study was conducted using the Environmental Footprint 3.0 methodology, while the calculations were performed with SimaPro V7.3 software.

The Life Cycle Impact Assessment (LCIA) process involves several steps, including the characterization of the data collected in the life cycle inventory (LCI) phase. In the LCIA process, collected LCI data is transformed within each impact category using "characterization factors" to generate "impact category indicators". These indicators quantify the contribution of each outcome to specific impact categories, enabling a standardized comparison of different environmental impacts.

The purpose of this step is to convert all streams classified for an impact into common units facilitating a meaningful comparison. The analysis focused on evaluating the innovative scenario S2 in a "conservative" manner. This means that the analysis always preferred the least favorable conditions in terms of environmental impacts. This conservative approach ensures that the assessment considers the worst-case scenario for the innovative approach. The results obtained from this comprehensive analysis depict two distinct scenarios, with Scenario 2 (S2) demonstrating significantly lower environmental impact compared to Scenario 1 (S1). The considerable difference in impacts indicates that, even under conservative assumptions and considering the least favorable conditions, the innovative approach (S2) is likely to have a much lower environmental footprint than the standard approach (S1). This suggests that uncertainties related to assumptions, inventory data and impact assessment methodology used in the study are unlikely to significantly impact the comparison between the two scenarios.

Results and discussion

Filler characterization

Filler grain size is a crucial factor in filled elastomers as it affects the mechanical behavior of composite materials. In order to perform an accurate comparison of different fillers, the range of particles size is reported in Fig. 2. It is evident that calcium carbonate has a narrower particle size distribution in the 32–45 μm range, with almost 60% of the particles falling within this range. On the other hand, the particle size distribution of EAF slag is broader, with approximately 15% of the particles being smaller than 32 μm, 30% in the 32–45 μm range, 25% in the 45–63 mm range, and another 25% in the 63–90 μm range.

The chemical composition of the EAF slag, as reported in Table 3, reveals that it is predominantly composed of iron oxide (Fe_2O_3) and calcium oxide (CaO), accounting for 40.6% and 26.4% of the slag, respectively. Silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) contribute 14.3% and

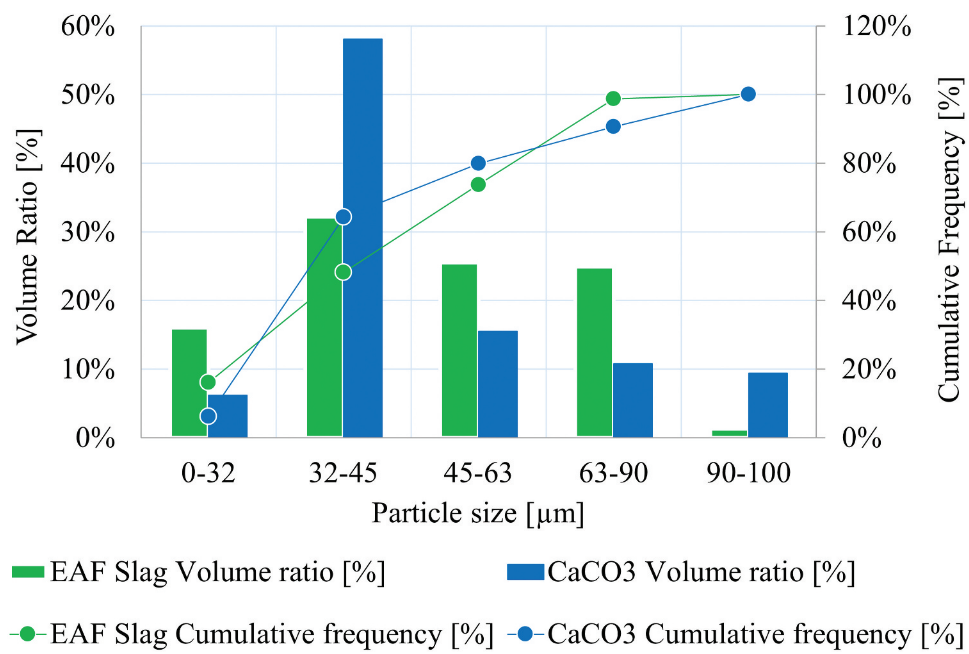
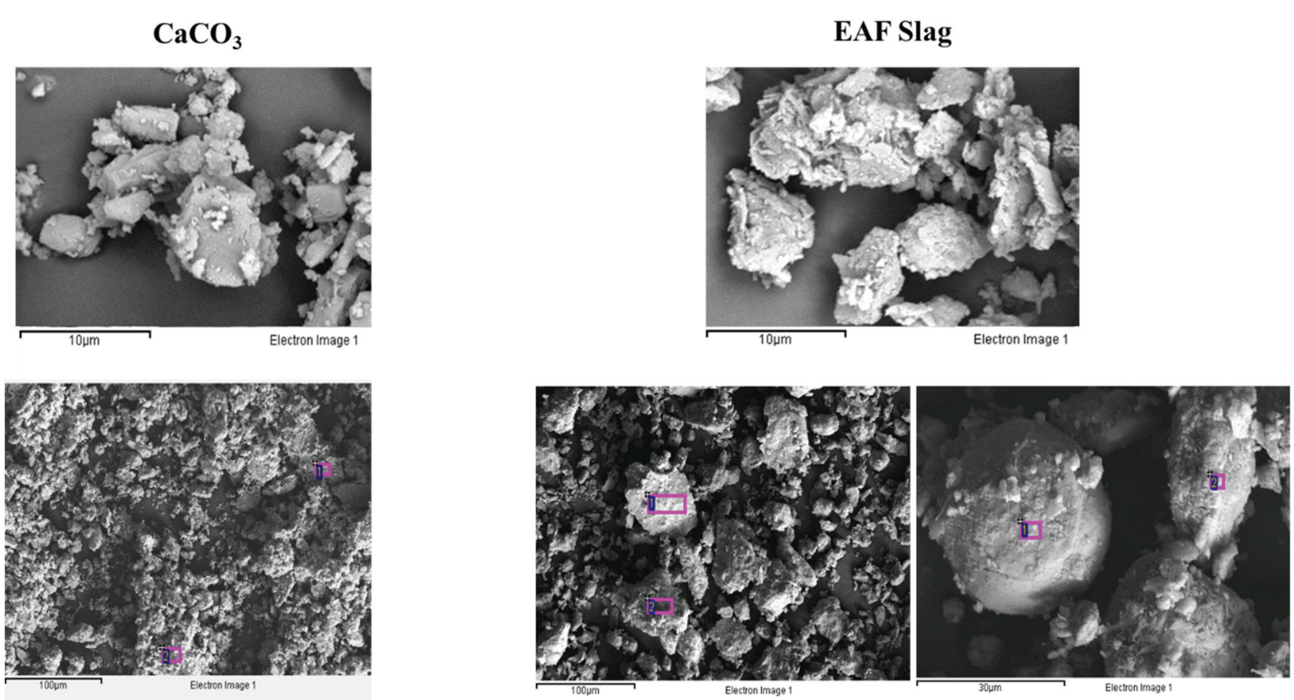


Figure 2. EAF slag and CaCO3 particle size frequency and cumulative frequency.



Spectrum	C	O	Ca
1	11	52	36
2	7	44	48

Spectrum	O	Mg	Al	Si	Ca	Ti	Cr	Mn	Fe
1	42	3	7	12	25	1		2	9
2	29	3	7	7	28		2	3	22

Spectrum	O	Mg	Al	Si	Ca	Cr	Mn	Fe
1	29	10	5		10	1	5	41
2	42	2	5	12	29		1	7

Figure 3. SEM images of $CaCO_3$ and EAF slag particles at different enlargements and EDXS analysis. All amounts are reported in weight%.

Table 3. EAF slag chemical composition determined by X-ray fluorescence spectroscopy (XRF) and basicity indexes. All amounts are reported in [%wt.].

SiO_2	Al_2O_3	Fe_2O_3	MnO	CaO	MgO	P_2O_5	TiO_2	Cr_2O_3
14,3	5,4	40,6	3,3	26,4	7,3	0,6	0,4	1,7
IB2		1,8		**IB4**			1,7	

5.4%, respectively, while other elements such as manganese oxide (MnO), magnesium oxide (MgO) and various trace elements are present in smaller quantities. The chemical composition of slag is intricately linked to the parameters of the steel production and the composition of smelted ferrous scraps. As reported in the literature,[35,36] the slag chemical composition plays a crucial role in influencing its leaching behavior. The leaching behavior, in turn, has implications for environmental impact of slag. Given this, the basicity index is a crucial parameter used to summarize the chemical composition of slag, providing insights into its leaching stability. In steelmaking, various methods are employed to determine the basicity indexes, with BI2 and BI4 are widely utilized. BI2 is a simpler formula defined as the CaO/SiO_2 ratio. This index, widely employed in steelmaking assessments, has been correlated with Cr leaching by several authors.[37,38] When BI2 is lower than 2 and there is sufficient MgO to form insoluble picrochromite ($MgO{\cdot}Cr_2O_3$), the slag tends to be less susceptible to Cr leaching.[39] However, it is also important to consider the contributions of Al_2O_3 and MgO that if present in low concentration (1–3%wt.) promotes the formation of unstable Cr-spinels and Brownmillerite (calcium-ferrite $4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$), main responsible to Cr and V leaching due to Al substitution.[40,41] Due to this, the more complete formula BI4 has been defined as $(CaO+MgO)/(SiO_2+Al_2O_3)$. Mombelli et - al.[39] found that BI4 lower than 2 is associated with the formation of stable spinels, leading to low Cr leaching. Tossavainen et al. suggested that a slag with BI4 higher than 1 May form a glassy phase if rapidly cooled, preventing the heavy metals leaching.[35] Table 4 shows the leaching test results. According to the forecasts defined by the basicity indices, the leaching of Cr and V is lower than the legal limits. This is noteworthy for both potential reuse and disposal as inert material. As regards Mo leaching, while literature did not define a correlation with other properties, it is acknowledged that Mo leaching is influenced by factors such as basicity and chemical composition.[40] The results indicate that Mo leaching may be reduced by rapid cooling, aligning with findings in the literature.[35]

The chemical composition of selected areas of calcium carbonate and slag particles was determined by SEM-EDS analysis. This analysis served to validate and confirm the XRF results obtained for the slag particles, as depicted in Fig. 3. Moreover, the SEM-EDS analysis facilitated a morphological comparison between the two fillers, calcium carbonate, and slag particles. The results revealed a strong resemblance between these fillers, both in terms of particle size and geometry.

Compound characterization

Rheometric parameters

The characterization of rheometric parameters is essential for a preliminary evaluation of the rubber compound processability. Dividing the rheometric curve into three phases, namely scorch time, vulcanization, and mechanical properties, provides a comprehensive understanding of the compound's behavior during processing and curing. Phase 1 provides information on the viscosity of the uncured compound, which refers to how easily it fills the mold cavities before vulcanization starts. Phase 2 focuses on the vulcanization kinetics, which refers to the speed at which the material completes the crosslinking process. In terms of the production process, it is desirable for the viscosity to be low and the scorch time to be long to ensure optimal mold filling. Once in position, a high crosslinking speed is necessary to shorten the cycle time and achieve cost savings. Transitioning into phase 3, the emphasis shifts toward assessing the mechanical properties of the cured compound.

Table 5 presents these rheometric parameters for NBR filled with EAF slag and $CaCO_3$. Increasing filler content results in initial and minimum torque due to increased viscosity; scorch times decrease, indicating a shorter curing time due to lower polymer fraction. Those findings are consistent with existing literature.[42–44] The experimental results highlight that the processability of slag filled NBR is comparable to that of $CaCO_3$ filled NBR at equal filler volume fraction. In particular, at 20%v/v slag filled NBR exhibits lower viscosity (related to MinT), slightly longer scorch times (Ts1 and Ts2) and curing kinetic (t50) accompanied by unchanged global curing time (t90). As last, form the maximum torque it is possible to predict a stiffer behavior of EAF slag filled NBR with respect to the $CaCO_3$ filled one.

Mechanical properties

Figure 4. shows the hardness of EAF slag filled NBR and $CaCO_3$ filled NBR at equal volume fraction, measured in SHA and mIRHD. As expected, an increase in filler content results in an increase in approximately 10% in SHA and 15% in mIRHD as an increasing content of rigid particles in a soft matrix increases the overall compound's hardness. This behavior aligns with well-known observations detailed in.[21] As regards the influence of different type of filler on the rubber compounds' hardness, no evident differences in the NBR

Table 4. Leaching test results.

				Italian limits for landfilling as inert waste[34]	Italian limits for material reuse[35]
pH [-]	11,58	±	0,1	-	5,5 < > 12,0
Electric conductivity [µs]	1107	±	10	-	-
Mo [mg/l]	0,073	±	0,003	<0,05	-
Cr [mg/l]	0,043	±	0,0007	<0,05	<0,05
V [mg/l]	0,006	±	0,0004	-	<0,25

Table 5. Rheometric parameters of standard NBR and $CaCO_3$ filled NBR and EAF slag filled NBR at 5, 10, 20% v/v. Initial torque (IT), minimum torque (MinT), time to reach torque 1 dN*m (Ts1) and 2 dN*m (Ts2), time to reach 50% and 90% of complete vulcanization (T50 and t90 respectively), and maximum torque (MaxT).

	Phase 1				Phase 2		Phase 3
	IT [dN*m]	MinT [dN*m]	Ts1 [sec]	Ts2 [sec]	t50 [sec]	t90 [sec]	MaxT [dN*m]
NBR Standard	4,20	1,48	32	39	63	106	18,04
NBR 5%$CaCO_3$	4,84	1,99	30	37	61	104	19,88
NBR 10%$CaCO_3$	5,47	2,3	28	34	58	97	22,27
NBR 20%$CaCO_3$	8,94	6,45	24	30	51	89	24,03
NBR 5% EAF slag	7,41	2	30	36	59	95	20,07
NBR 10% EAF slag	6,03	2,33	29	35	58	92	21,92
NBR 20% EAF slag	6,71	3,19	26	31	56	89	27,11

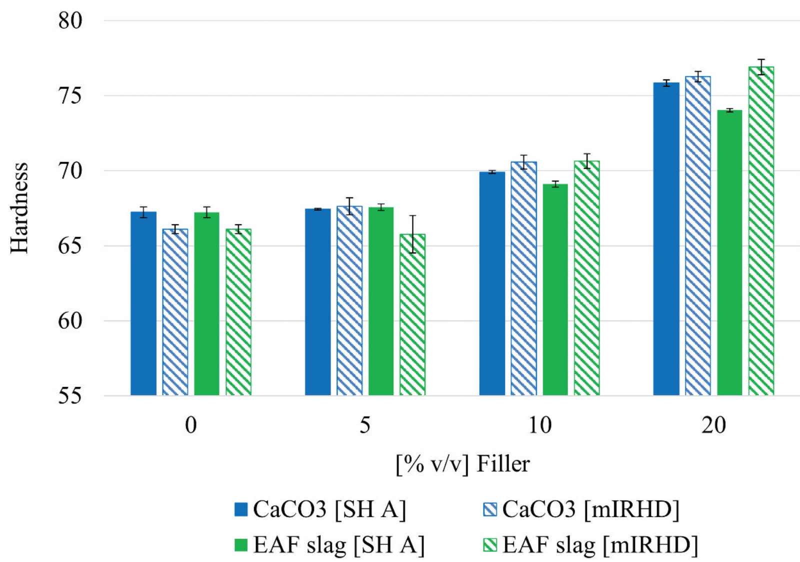


Figure 4. Hardness results in shore a (solid) and mIRHD (dotted) of standard NBR and $CaCO_3$ filled NBR and EAF slag filled NBR at 5, 10, 20% v/v.

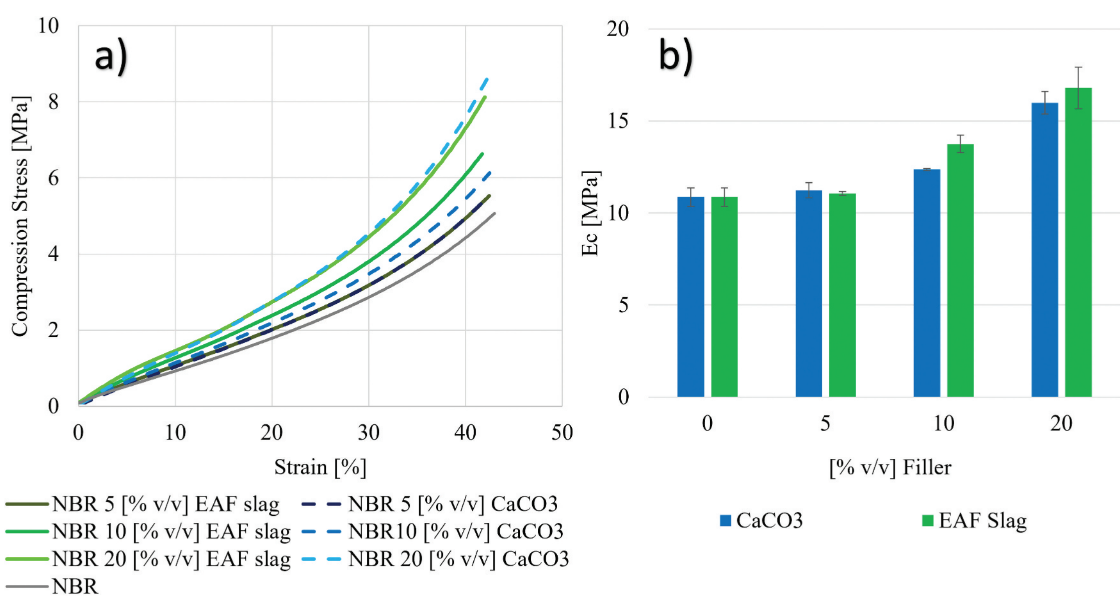


Figure 5. (a) Compression stress–strain curve of a representative sample of standard NBR and $CaCO_3$ filled NBR (solid lines) and EAF slag filled NBR (dotted lines) at 5, 10, 20% v/v. (b) Compressive elastic modulus.

composite's hardness can be appreciated considering that the hardness tolerance of a rubber compound in the rubber industry is ± 5 hardness point.

Figure 5. shows the compression stress–strain curve for NBR filled with EAF slag and $CaCO_3$ at an equal volume fraction. It is evident that the amount of stress needed to achieve a particular level of strain increases in proportion to the amount of filler present. The increase in compression strength from approximately 4,5 MPa to 7,4 MPa with a filler content of 20 [% v/v] demonstrates the effectiveness of fillers in reinforcing the NBR compound. The increase in compression strength is essential for applications where the material is exposed to compressive loads, such as seals, gaskets, and vibration damping components. This trend aligns with the general behavior observed when rigid filler particles are introduced, leading to increased stiffness of the rubber compound, as evidenced also in the rheometric parameter (MaxT in Table 5) and in hardness measurements (Fig. 4). The elastic modulus increases by 45% with filler content 20% v/v. Notably, no significant differences are appreciable between EAF slag and $CaCO_3$ regarding their impact on compression stress-strain behavior, suggesting that, in terms of compression properties, the choice of filler may not significantly influence the material's response within the studied volume fraction.

The rubber compound's ability to return to its original shape after being deformed has been assessed using permanent set measurements under compression conditions. This evaluation process is crucial for understanding the material's performance and durability in practical applications. Increasing the volume fraction of fillers does not lead to a decrease in permanent set, which consistently remains below 15%, a value widely regarded as excellent (see Fig. 6). This exception is observed in EAF slag filled NBR at 20% v/v, where the permanent set reaches 17%. This effect on the long-term performance of the rubber compound could be attributed to the metal oxides present in the EAF slag, which, according to existing literature, can serve as crosslinking agents.[45,46] In particular, with a slag content exceeding 10% [v/v], the metal oxides in EAF slag can act as aging components. Investigating this effect further could provide insights into the possibility of reducing the amount of crosslink agent and/or activators in the standard rubber compounds.

In Fig. 7a, the tensile stress–strain curve reveals that the presence of filler reduces both stress and the strain at break, attributed to the increasing amount of rigid particles restricting the polymer's deformability along the direction of maximum stress. This phenomenon generates local over-stresses, contributing to premature break of the compound.[21]

The tensile curves of EAF slag filled NBR and $CaCO_3$ filled NBR at 5% exhibit significant overlap, diverging more with higher filler amounts. Notably, at 10% filler content, NBR filled with slag demonstrates a higher strain at break compared to $CaCO_3$filled NBR an equal stress at break. At 20% filler content, NBR filled with slag shows a slightly lower stress at break (9,2 MPa EAF slag, 11 MPa $CaCO_3$) but a substantially higher strain at break (+40%). In Fig. 7b, the elastic modulus of $CaCO_3$ filled NBR and EAF slag filled NBR at 0, 5, 10, and 20% v/v is shown. As expected, the rubber compound's modulus increases with rising filler content. Up to a filler content of 10%v/v, both fillers demonstrate an identical elastic modulus. However, at 20%v/v filler content, NBR compound filled with $CaCO_3$ shows a slightly higher elastic modulus than that filled with EAF slag, corresponding to a notable reduction in strain at break.

Environmental impact

A life cycle impact assessment (LCIA) analysis was conducted based on inventory data to quantify the environmental impact associated with producing 1 dm^3 of a $CaCO_3$-filled NBR in the Standard Scenario (S1) compared to using EAF slag as filler in the Innovative Scenario (S2). The latter scenario involves the avoidance of slag landfilling and $CaCO_3$ production. Table 6 shows the environmental impact in terms of characterization results for each impact category in both scenarios, while Fig. 8 provides a comparative representation, expressing the impact percentage-wise, with the most impactful scenario assumed as 100% and the other one proportionally scaled.

The LCA outcomes underscore a discernible environmental superiority of EAF slag over $CaCO_3$ across a spectrum of

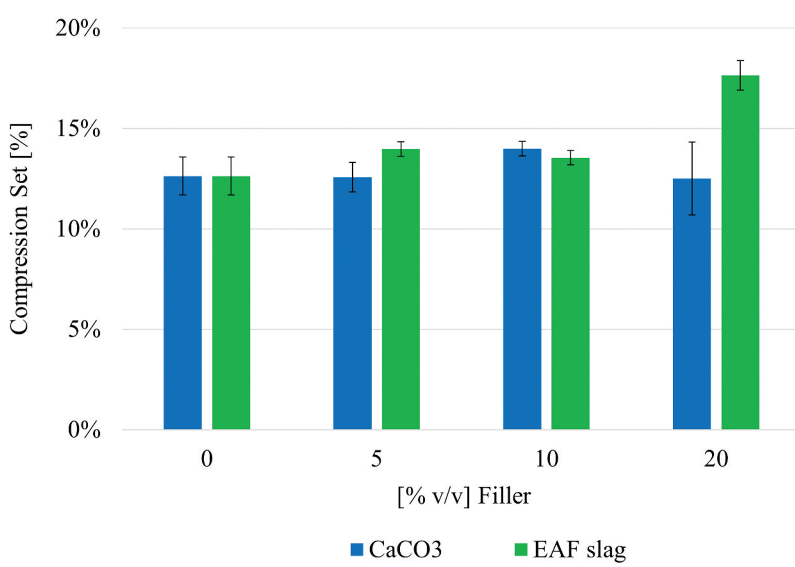


Figure 6. Compression set of $CaCO_3$ filled NBR and EAF slag filled NBR at 0, 5, 10, 20% v/v.

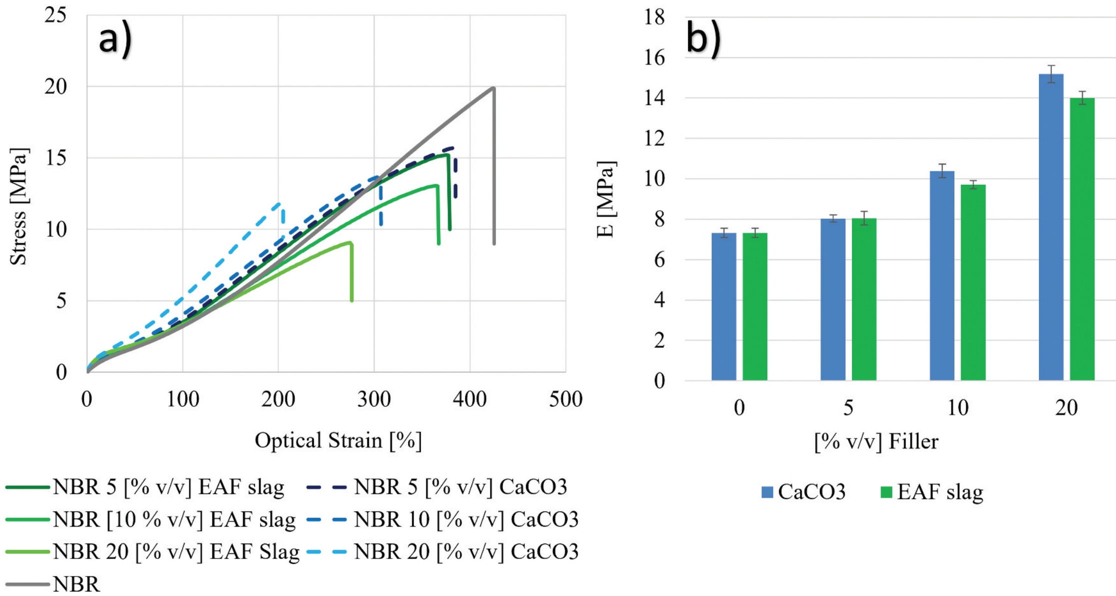


Figure 7. (a) Tensile stress strain curve of a representative sample of standard NBR and $CaCO_3$ filled NBR (dotted lines) and EAF slag filled NBR (solid lines) at 5, 10, 20% v/v; (b) tensile elastic modulus.

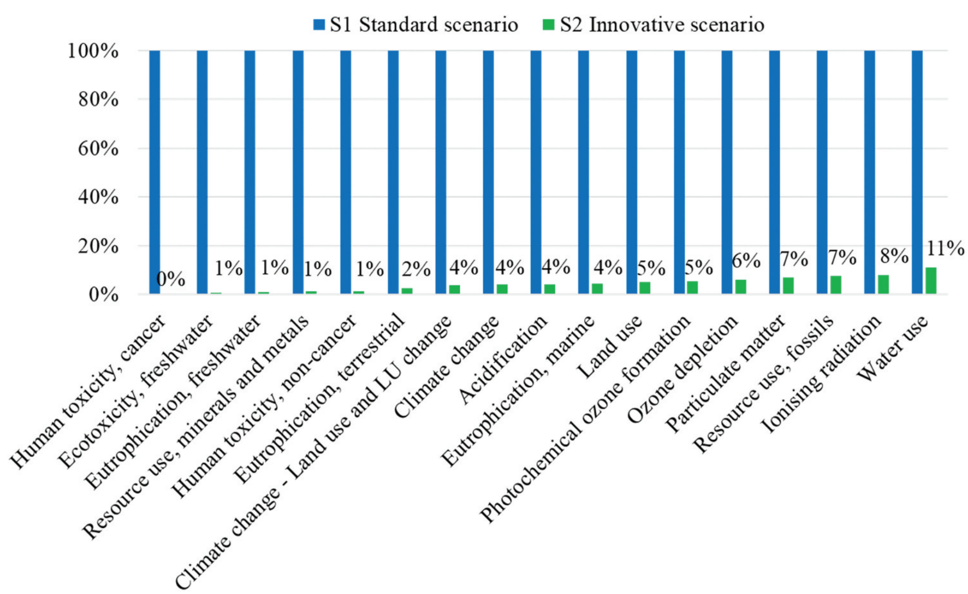


Figure 8. Contribution analysis related to the characterization results for impact categories of $CaCO_3$-filled NBR (S1 standard scenario) and EAF slag-filled NBR at 20%v/v (S2 innovative scenario).

impact categories. Particularly noteworthy are the profound reductions in "Human toxicity" impacts, encompassing both carcinogenic and non-carcinogenic facets, as well as in "Ecotoxicity, freshwater", "Eutrophication, freshwater", and "Resource use, minerals and metals The attainment of over 99% lower impacts when using EAF slag as a filler is indicative of its pronounced mitigating effect on chemical emissions, thereby averting deleterious consequences for human health and freshwater ecosystems, notably through the circumvention of slag landfilling. Furthermore, compelling advantages, surpassing the 90% reduction threshold, are conspicuous in fundamental categories like "Climate change", "Particulate matter" formation, and "Land use". Transitioning from $CaCO_3$ to EAF slag would substantially decrease greenhouse gas emissions, mitigating air pollutant generation, and diminishing fossil fuel utilization associated with filler material extraction and production processes.

While a reduction of nearly 90% is observed in the category of "Water use", EAF slag consistently outperforms $CaCO_3$ across diverse impact categories related to air quality, marine habitats, radiation exposure, soil quality, and water scarcity. At equal compounds performance, EAF slag reduces environmental impacts across all investigated indicators, with especially sizable reductions in the critical categories of human health, ecosystem quality, climate change, and resource use. These findings underscore the comprehensive environmental advantages of EAF slag throughout the life cycle, stemming from its role in obviating the need for virgin mineral extraction and to reducing chemical emissions during both processing and end-of-life phases. In essence, the LCA findings

Table 6. Characterization results for impact categories of CaCO3-filled NBR (S1 standard scenario) and EAF slag-filled NBR at 20%v/v (S2 innovative scenario).

Category of impact	Definition	S1	S2
Acidification [mol H^+ eq]	Indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulfur oxides	2,01E−03	8,25E−05
Climate change [kg CO_2 eq]	Indicator of potential global warming due to emissions of greenhouse gases to the air.	0,5	0,02
Ecotoxicity, freshwater [CTUe]	Impact of the potential harm or damage caused to freshwater ecosystems due to the release of chemical substances into the environment. It quantifies the ecological impact of these substances on aquatic life and the overall health and balance of freshwater ecosystems.	17,32	0,11
Particulate matter [disease inc.]	Indicator of the potential incidence of disease due to particulate matter emissions.	1,89E−08	1,28E−09
Eutrophication, marine [kg N eq]	Indicator of the enrichment of the marine ecosystem with nutritional elements, due to the emission of nitrogen-containing compounds.	4,91E−04	2,20E−05
Eutrophication, freshwater [kg P eq]	Indicator of the enrichment of the freshwater ecosystem with nutritional elements, due to the emission of nitrogen or phosphor-containing compounds.	2,64E−04	2,61E−06
Eutrophication, terrestrial [mol N eq]	Indicator of the enrichment of the terrestrial ecosystem with nutritional elements, due to the emission of nitrogen-containing compounds.	0,01	2,37E−04
Human toxicity, cancer [CTUh]	Impact on humans of cancer toxic substances emitted to the environment.	1,25E−07	9,06E−12
Human toxicity, non-cancer [CTUh]	Impact on humans of non-cancer toxic substances emitted to the environment.	1,48E−08	1,89E−10
Ionising radiation [kBq U-235 eq]	Damage to human health and ecosystems linked to the emissions of radionuclides.	0,02	1,60E−03
Land use [Pt]	Measure of the changes in soil quality (Biotic production, Erosion resistance, Mechanical filtration).	2,79	0,14
Ozone depletion [kg CFC11 eq]	Indicator of emissions to air that causes the destruction of the stratospheric ozone layer.	8,85E−09	5,33E−10
Photochemical ozone formation [kg NMVOC eq]	Indicator of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalyzed by sunlight.	1,87E−03	9,88E−05
Resource use, fossils [MJ]	Indicator of the depletion of natural fossil fuel resources.	4,86	0,36
Resource use, minerals and metals [kg Sb eq]	Indicator of the depletion of natural non-fossil resources.	5,08E−06	6,30E−08
Water use [m^3 depriv.]	Indicator of the relative amount of water used, based on regionalized water scarcity factors.	0,09	0,01

unequivocally support the strategic transition from $CaCO_3$ to metallurgical slag waste as a sustainable alternative filler material, underlining profound reductions in environmental impacts, especially in critical domains such as human health, ecosystem quality, climate change, and resource utilization.

Conclusion

This study provides substantial evidence supporting the viability and sustainability of EAF slag as an alternative to conventional calcium carbonate filler in NBR composites. The findings demonstrate that EAF slag, predominantly composed of 40,6% of iron oxide and 26,4% calcium oxide, exhibits morphological characteristics similar to calcium carbonate when used as a filler.

Rheometric analysis demonstrates comparable processability for NBR filled with EAF slag and NBR filled with calcium carbonate at equivalent filler volume fractions. Additionally, assessments of mechanical properties, including hardness, compression stress-strain, and tensile stress-strain, indicate no significant divergence between the two types of fillers. Notably, NBR filled with EAF slag at 20% v/v exhibits a higher strain at break (40% increase) compared to its calcium carbonate-filled counterpart (280% and 200%, respectively), suggesting potential performance advantages. Increasing the filler content results in an increase in hardness and elastic modulus of the compounds. Specifically, hardness measured in Shore A increases by approximately 10% from 65 SHA at 0% filler to 75 SHA at 20% filler volume fraction. Similarly, the mIRHD increases by around 15% from 63 mIRHD to 73 mIRHD across the same filler range. The rubber compound's elastic modulus, related to its stiffness, also rises incrementally with higher volumes of filler. The compressive elastic modulus grows from 11 MPa to 15 MPa at 20% filler content, representing a 36% increase. Likewise, the tensile elastic modulus escalates from 1,1 MPa to 3,6 MPa at 20 [% v/v] filler, corresponding to a 227% increase. These quantitative augmentations in hardness and elastic stiffness are aligned with expected behavior when rigid filler particles are embedded within the polymer matrix.

The environmental impact assessment conducted in this study quantifies the environmental benefits associated with incorporating EAF slag as a filler in NBR composites. This assessment considers both the avoidance of slag landfilling and the reduced need for calcium carbonate production. The results demonstrate a minimum reduction of 89% across all impact categories, with human toxicity, ecotoxicity, eutrophication, and resource use specifically witnessing a remarkable reduction of 99%. These findings substantiate that the utilization of EAF slag as a filler contributes to sustainable materials management, leading to reduced CO_2 emissions and enhanced resource efficiency.

The study demonstrates the feasibility and environmental benefits of reusing electric arc furnace slag as a filler material, promoting industrial symbiosis approaches that manage steel industry waste and reduce dependence on virgin resources. The results provide compelling evidence for rubber product manufacturers to incorporate this by-product into their formulations instead of standard fillers such as calcium carbonate. The environmental benefits can incentivize industries to reexamine their material flows for circular integration opportunities. This research sets the foundation and impetus for institutes, corporations, and policy bodies to transform sustainable intentions into practical reality.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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