In: Light Metals 2025. TMS 2025 154th Annual Meeting & Exhibition, Las Vegas, NV, USA.
The Minerals, Metals & Materials Series, pp.1218-1225
DOI:10.1007/978-3-031-80676-6_151

Environmental Impact Lifecycle Assessment of Green Sand Moulding in Foundries

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Abstract. The metal casting industry faces significant challenges in reducing its environmental impact. This paper presents a study aimed at evaluating and minimizing the environmental effects of green sand moulding processes. The project uses advanced Life Cycle Assessment (LCA) methodologies, specifically the ReCiPe method, to analyse the entire lifecycle of moulding sand, from extraction to disposal. The study measures emissions during the metal pouring process and identifies key contributors to greenhouse gas emissions. By incorporating sustainable binder technologies and optimizing sand reclamation processes, the project suggests practical strategies for reducing the carbon footprint of foundries. The outcomes include a detailed lifecycle inventory report, an impact assessment highlighting critical areas for intervention, and a practical guide for implementing emission reduction strategies. This research supports global Net Zero targets and offers a model for sustainable practices in the foundry industry. The findings provide essential insights and feasible strategies for foundries to achieve substantial environmental impact reductions, contributing to a more sustainable future in metal casting. This comprehensive approach ensures that the proposed solutions are both effective and scalable, aligning with broader environmental sustainability goals.

Keywords: Shaping and Forming, Sustainability, Extraction and Processing, Life Cycle Assessment, Green Sand Moulding, Carbon-Free Greensand Moulding Systems

1 Introduction

The metal casting industry plays a critical role in global manufacturing, contributing significantly to sectors such as automotive, aerospace, and construction. However, the environmental impact of green sand moulding, which is widely used due to its cost-effectiveness and versatility, poses significant challenges. Green sand moulding involves using a mixture of sand, clay, water, and binders to form moulds for metal casting [1]. Despite its advantages, this process is associated with considerable environmental burdens, including high energy consumption, significant greenhouse gas emissions, and waste generation [2, 3]. Addressing these environmental impacts has become a priority for the industry, driving research into more sustainable practices.

Life Cycle Assessment (LCA) methodologies, such as the ReCiPe method, provide a comprehensive evaluation of the environmental impacts of green sand moulding across its entire lifecycle, from raw material extraction to disposal [4]. The ReCiPe method is a comprehensive Life Cycle Impact Assessment (LCIA) approach widely used to evaluate the environmental impacts of products and processes [5]. It integrates both midpoint and endpoint analyses, translating complex life cycle inventory data into 18 midpoint impact categories such as climate change, human toxicity, and resource depletion and further aggregating them into three endpoint categories: human health, ecosystem quality, and resource scarcity. By applying ReCiPe, critical stages contributing most to environmental degradation in foundry operations like emissions from the metal pouring process and waste generated from spent sand can be identified and quantified. This detailed assessment enables the development of targeted strategies to reduce the carbon footprint and enhance the overall environmental performance of foundries by focusing on specific impact categories where significant improvements can be made.

One key area of research is the comparison of green sand moulding processes using traditional additives like coal dust versus newer materials such as Moldcote refractory material. Coal dust has been a conventional choice for improving the surface finish of castings and enhancing the mould's properties, but it also contributes to significant emissions and environmental concerns due to its carbon content [6]. In contrast, refractory material offers an alternative that can reduce emissions and improve the environmental performance of the moulding process. Studies have shown that using refractory additives can lead to lower levels of volatile organic compounds (VOCs) and reduced particulate emissions compared to coal dust [7]. This comparison underscores the potential of alternative materials to improve the sustainability of green sand moulding.

Sustainable binder technologies and optimized sand reclamation processes are also crucial strategies for reducing the environmental impact of green sand moulding. Innovations in binder technology, including organic and inorganic options with lower environmental impacts, are being explored to reduce emissions and enhance the recyclability of moulding sand [8, 9]. Advanced sand reclamation techniques allow for the reuse of sand in the moulding and core making process, minimizing waste and reducing the need for new sand extraction [10]. These approaches align with broader efforts to make the green sand moulding process more sustainable.

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The final published version (version of record) is available online at DOI:10.1007/978-3-031-80676-6_151. Please refer to any applicable publisher terms of use.

Despite the progress in sustainable technologies, there remains a gap in comprehensive studies that evaluate the full environmental impact of green sand moulding processes using advanced LCA methods like ReCiPe. Most existing research focuses on individual aspects, such as emissions or energy use, without providing an integrated analysis of all lifecycle stages [11]. Additionally, while refractory additive materials show promise in reducing emissions compared to coal dust, further empirical studies are needed to validate their performance in operational foundries [12]. This research seeks to fill these gaps by conducting a holistic lifecycle assessment of green sand moulding and providing practical recommendations for adopting more sustainable practices in the foundry industry [13].

A review of existing literature highlights the environmental challenges associated with traditional green sand moulding, particularly when using coal dust. LCA studies frequently report high emissions and energy consumption linked to the use of coal dust as an additive [14]. The application of advanced LCA methods like ReCiPe remains limited in this context, which constrains the ability to fully assess the environmental impacts of alternative materials like Moldcote across the entire lifecycle. Furthermore, while alternative materials and advanced reclamation techniques are explored in some studies, their practical implementation in real-world foundries remains under-evaluated.

Greenhouse gas emissions are categorized into three scopes according to the Greenhouse Gas Protocol [15]: Scope 1 involves direct emissions from sources owned or controlled by an organization, such as company vehicles and on-site fuel combustion; Scope 2 includes indirect emissions from the generation of purchased electricity, steam, heating, and cooling consumed by the organization; and Scope 3 encompasses all other indirect emissions in the organization's value chain, including activities like procurement, waste disposal, transportation, and business travel. This paper focuses on a Scope 2 analysis of indirect greenhouse gas emissions from purchased energy, as illustrated in Fig. 1 [15]. The emphasis on Scope 2 is chosen because energy consumption constitutes a significant portion of the organization's carbon footprint and can be directly influenced through energy usage and procurement decisions. While Scope 1 emissions are minimal due to limited direct fuel use, and Scope 3 emissions involve complex factors beyond immediate control, Scope 2 offers practical opportunities for reduction. By quantifying these emissions which occur at the utility provider level but result from the organization's energy demand the study aims to identify actionable strategies for emission reductions, such as improving energy efficiency and adopting renewable energy sources, thereby advancing sustainability objectives.

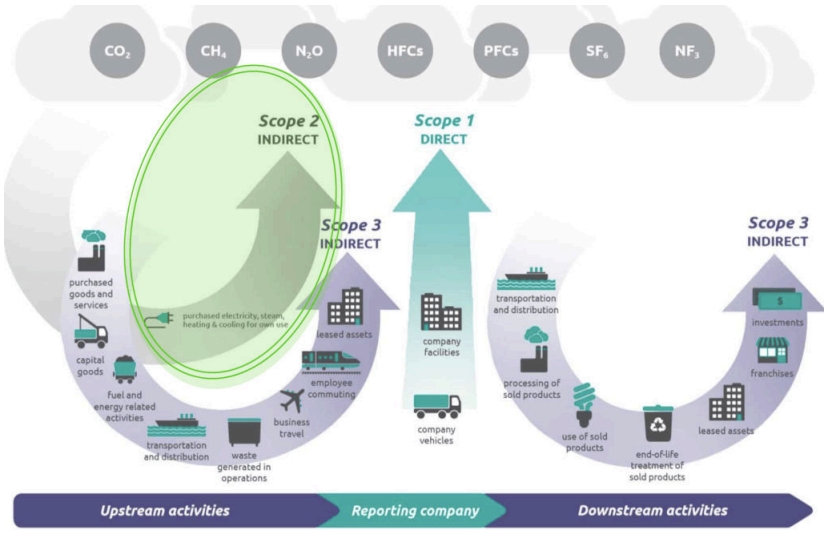


Figure 1 Categorization of greenhouse gas emissions into Scope 1, 2, and 3 [15].

To advance the sustainability of green sand moulding, more comprehensive assessments are needed ones that integrate advanced LCA methodologies and directly compare the environmental impacts of different materials, such as coal dust and Moldcote refractory material. This study aims to bridge these gaps, providing the foundry industry with insights and strategies to reduce its environmental footprint through informed material choices and improved practices.

2 Methodology

This study evaluates the environmental impact of green sand moulding by comparing traditional carbon-based systems with a carbon-free alternative using Moldcote refractory materials. A LCA was conducted using the ReCiPe method, analyzing environmental impacts from a cradle-to-gate perspective in accordance with ISO

14040 and 14044 standards, where any impact on dumping is or is not included in the analysis [16, 17]. The goal is to compare the environmental impacts of carbon-based moulding systems, which use coal dust, with carbon-free systems using Moldcote.

The system boundaries include raw material extraction, sand preparation, moulding, pouring, cooling, and sand reclamation. Data were sourced from a European ferrous foundry and supplemented with information from LCA databases like Ecoinvent, focusing on energy use, emissions, and waste.

A Scope 2 analysis was conducted to assess indirect greenhouse gas emissions from purchased electricity, steam, heating, and cooling. Emission factors from regional energy grids were applied to foundry energy consumption data to calculate total Scope 2 emissions, identifying opportunities for reduction through energy efficiency and renewable energy integration.

LCA models were developed using SimaPro software [18], incorporating primary data from industrial trials and secondary data from literature and LCA databases. The ReCiPe method assessed impacts in categories like climate change, with a focus on Global Warming Potential (GWP) emissions.

The study compares carbon-based systems using coal dust with carbon-free systems using Moldcote, evaluating parameters such as material requirements and thermal degradation per cycle, as seen in Table 1 below.

Table *1*. Carbon base and Carbon-Free system parameters.

Parameter	Carbon-based Greensand System	Carbon-free Greensand System
System Requirement	Carbon Requirement	MOLDCOTE TN100 Requirement
Total Target (%)	2.0%	0.60%
Thermal Degradation per Cycle (%)	1.0% of total carbon	<0.9% of total refractory

Key performance indicators (KPIs) such as GWP emissions (CO_2-equivalent) and energy consumption were used to compare the environmental impacts of both systems, highlighting the potential benefits of Moldcote in reducing emissions.

3 Green Sand Moulding Processes

3.1 Process Maps

The process mapping for the Carbon-based and Carbon-free Greensand Moulding Systems highlights key differences in materials and environmental impacts. In the Carbon-based System (S1), in Fig. 2, silica sand is mixed with bentonite clay, water, and carbon additives like coal dust, which are mulled and used for mould making. During metal pouring, burn-out of clay and carbon generates emissions and waste, with sand reclamation and dust extraction managing impurities and reclaiming sand.

The Carbon-free System (S2) using Moldcote, in Fig. 2, follows a similar flow but replaces carbon additives with Moldcote refractory materials. This change reduces carbon emissions and optimizes sand usage. The process includes sand preparation, mulling, mould making, and metal pouring, with thermal degradation waste limited to clay and refractory materials. Both systems employ sand reclamation and dust extraction, but the Carbon-free System achieves greater sustainability by eliminating carbon-related emissions.

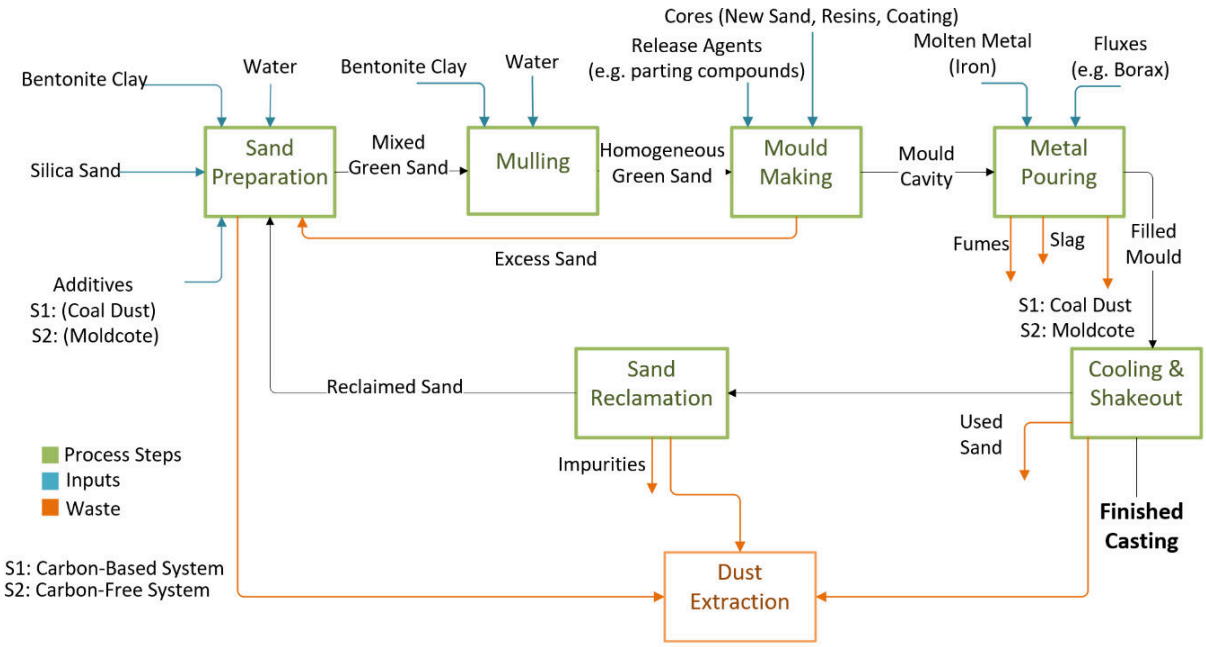


Figure 2 Carbon-based (S1) and Carbon-Free (S2) system process map.

The process maps highlight that the Carbon-based (S1) Greensand Moulding System relies on carbon additives, resulting in significant carbon burn-out and related emissions. In contrast, the Carbon-free System (S2) using Moldcote refractories eliminates carbon additives, reducing burn-out waste and emissions associated with carbon. By optimizing sand reclamation and minimizing waste, the Carbon-free System offers a more efficient and environmentally friendly alternative, aligning with the industry's goals of reducing its carbon footprint and enhancing sustainability in foundry operations.

3.2 Inventory Analysis

The inventory analysis of the Carbon-free and Carbon-based Greensand Systems provides detailed insights into the material flows and resource use across various process steps. In the Carbon-free System, inputs include start-up sand, mixed green sand, refractory additives, and molten metal. Key outputs are homogeneous green sand, filled moulds, finished castings, reclaimed sand, and waste from impurities. The analysis shows efficient use of sand reclamation, with a significant amount of used sand being reclaimed and reused, minimizing waste generation.

$$Input\ Material\ Mass = Mass\ Produced \times Material\ Utilization\ Factor \quad (1)$$

$$Consumed = Mass\ Produced \times Energy\ Intensity\ Factor \quad (2)$$

$$Equivalent\ CO2\ Emission = Mass\ Produced \times CO2\ Intensity\ Factor \quad (3)$$

Table 2. Carbon-based and Carbon-Free system inputs and outputs inventory analysis [19-21].

Both Systems				
Process Step	Inputs	Value (tonnes/yr)	Outputs	Value (tonnes/yr)
Raw Material	Sart-Up amount	360	-	-
Sand Preparation	Sand (Start Up)	360	Mixed Green Sand	169701
Mulling	Mixed Green Sand	169793	Homogeneous Green Sand	16 793
	Additives	92		
Mould Making	Homogeneous Green Sand	174375	Moulds	17 375
	Cores (New Sand)	14575	Excess Sand	14575

Metal Pouring	Moulds	174375	Filled Mould	19 425
	Molten Iron	18015	Fumes (VOCs, Nox, etc.)	Not Specified
	Thermal Degraded Comp. (Carbon-Based/Carbon-Free)	35/9	Waste	35/9
Cooling & Shakeout	Filled Mould	19390	Finished Casting	7206
			Used Sand	18219
Sand Reclamation	Used Sand	18219	Reclaimed Sand	16004
			Impurities	2885
Dust Extraction	Impurities	2953	Waste	2953

Table 3. Carbon-based and Carbon-Free system energy consumption and carbon footpriint inventory analysis [19-21].

	Carbon-Based System		Carbon-Free System	
Process Step	Energy Consumption (GJ/yr)	Carbon Footprint (ton CO_2e)	Energy Consumption (GJ/ton)	Carbon Footprint (ton CO_2e)
Raw Material	403	1278	195	619
Sand Preparation	183	64	183	64
Mulling	35	12	35	12
Mould Making	54	19	54	19
Metal Pouring	42	1015	42	16
Cooling & Shakeout	64	22	64	22
Sand Reclamation	150	52	150	52

The table compares the inputs, outputs, energy consumption, and carbon footprint of the Carbon-Based and Carbon-Free Systems in a foundry. Inputs and outputs are largely the same for both systems, indicating similar operations in sand preparation, mulling, mould making, metal pouring, cooling, and sand reclamation.

The main difference between the systems is the additives: the Carbon-Based System uses more carbon additives, while the Carbon-Free System uses a lower-carbon alternative. Both systems have similar energy consumption, but the Carbon-Based System has a higher carbon footprint due to CO_2 emissions from these additives. In the metal pouring step, thermally degraded components contribute to emissions, with overall losses, including de-dusting and waste sand, leading to carbon footprints of 5,116 tonnes CO_2e for S1 and 2,463 tonnes CO_2e for S2. The Carbon-Free System, therefore, achieves a lower carbon footprint despite similar energy usage.

4 Life Cycle Assessment Results

The results section provides an analysis of the Carbon-free and Carbon-based Greensand Moulding Systems, focusing on material flows, resource efficiency, and environmental impacts. Based on the functional unit of producing 7,206 tonnes of finished castings per year, the inventory analysis compares key inputs such as sand and additives, and outputs like reclaimed sand and waste. The results highlight differences in material use, sand reclamation efficiency, and waste generation, offering insights into each system's sustainability performance and potential areas for improvement.

The energy consumption across different process stages for both the Carbon-based and Carbon-free systems shows identical results, with no significant differences observed in compacting, handling, pouring, cooling, and sand reclamation processes. This similarity in energy use is attributed to the fact that both systems employ the same fundamental equipment and operational parameters, with only the material additives differing between them. The energy demands of these processes are largely determined by the mechanical actions and heat requirements, which remain consistent regardless of the type of additive used in the moulding sand.

To accurately capture the full environmental impact, the endpoint indicators were reported. That is because they provide a more comprehensive view of the overall environmental burden, including the combined effects on human health, ecosystems, and resource depletion.

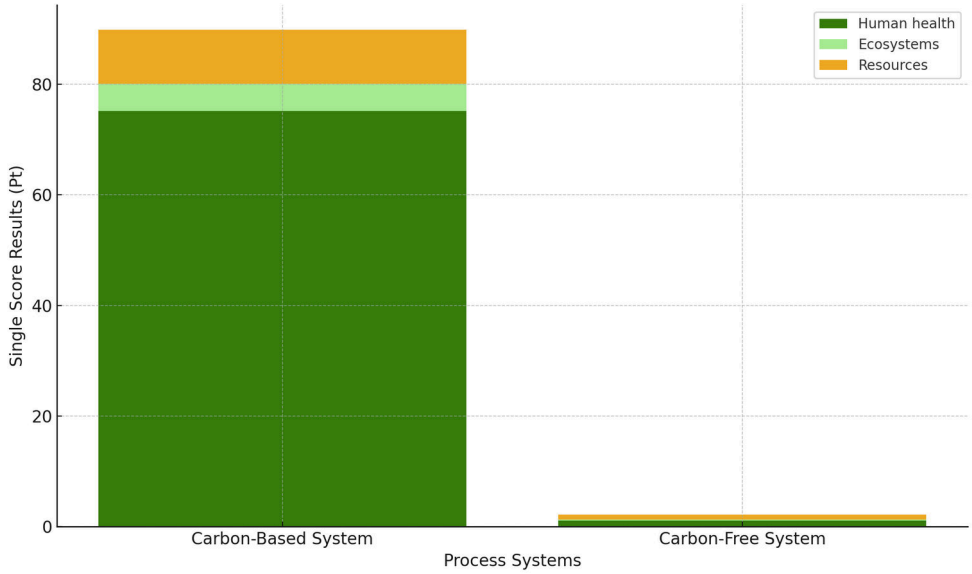


Figure 3 Weighting (single score) comparative between Carbon-base and Carbon-free systems.

Fig. 3 presents the weighting (single score) comparison between the Carbon-Based and Carbon-Free Systems, calculated using the ReCiPe endpoint method. The single score aggregates the environmental impacts across all categories into a single metric expressed in points (Pt), facilitating an overall comparison of the systems' environmental performance. The results indicate that the Carbon-Free System has a significantly lower single score than the Carbon-Based System, demonstrating its superior environmental performance.

The reduction in the single score for the Carbon-Free System is primarily attributed to the elimination of coal dust. In the Carbon-Based System, coal dust combustion during the metal pouring process releases substantial amounts of CO_2, volatile organic compounds (VOCs), and benzene, toluene, and xylene (BTX) emissions. These pollutants contribute extensively to human health impacts due to increased risks of respiratory diseases and cancer, as well as to ecosystem quality degradation through acidification and ecotoxicity. The Carbon-Free System avoids these emissions, resulting in cleaner production and significantly reduced environmental burdens.

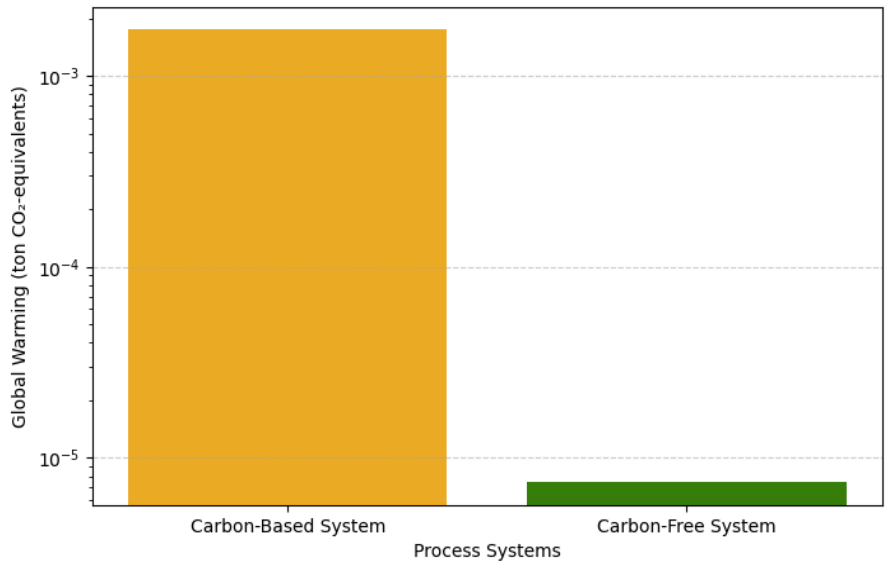


Figure 4 Total GWP comparison results of Carbon-Based and Carbon-Free systems from cradle to gate in logarithmic scale.

Fig. 4 illustrates the Global Warming Potential (GWP) in kg CO_2-equivalents for the Carbon-Based and Carbon-Free Systems from a cradle-to-gate perspective, encompassing all stages from raw material extraction to the end of the process, in logarithmic scale for better visualisation. The results highlight a stark contrast between the two systems, with the Carbon-Based System showing significantly higher GWP, compared to the Carbon-Free System, which has a negligible GWP impact.

This significant difference is largely due to the combustion of coal dust in the Carbon-Based System during the moulding and casting processes. The burning of coal dust releases CO_2 and other pollutants such as VOCs and BTX, which contribute extensively to global warming and other environmental impacts. These emissions are generated throughout the lifecycle stages, amplifying the overall carbon footprint of the Carbon-Based System.

In contrast, the Carbon-Free System, utilizing Moldcote, eliminates the need for carbonaceous additives, thereby preventing the release of CO_2 and associated pollutants. As a result, the Carbon-Free System maintains a minimal GWP impact across all lifecycle stages. This substantial reduction in greenhouse gas emissions underscores the effectiveness of the Carbon-Free System in mitigating climate change impacts and reinforces the importance of adopting carbon-free technologies in foundry operations to enhance sustainability. The cradle-to-gate analysis clearly demonstrates the environmental benefits of transitioning away from carbon-based materials, providing a compelling case for the industry's shift towards cleaner alternatives.

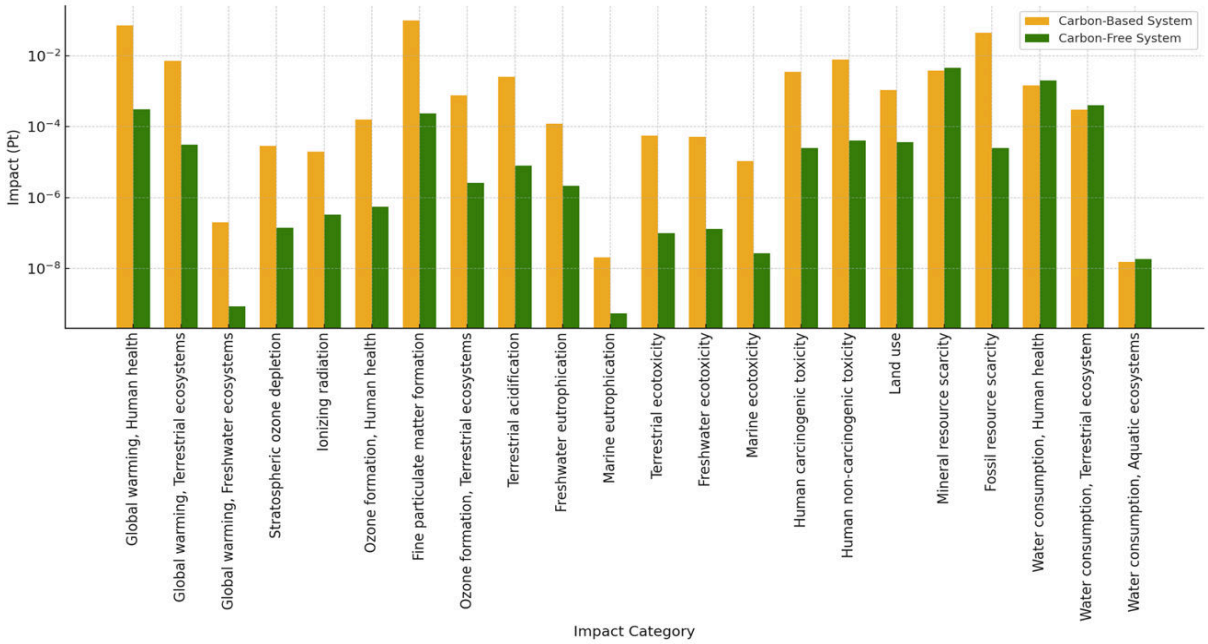


Figure 5 Normalised impact category results of the Carbon-Based and Carbon-Free systems both in logarithmic scale.

Fig. 5 presents the normalized impact category results for both systems across various environmental impact categories defined by the ReCiPe endpoint method. Normalization involves expressing the impacts relative to a reference situation, allowing for a meaningful comparison across different categories. The use of a logarithmic scale reveals orders of magnitude differences between the two systems, particularly in categories such as human toxicity, terrestrial ecotoxicity, and freshwater ecotoxicity.

The Carbon-Based System shows significantly higher impacts in these categories due to the emissions associated with coal dust combustion. For instance, human toxicity impacts are elevated because of exposure to harmful substances like heavy metals and organic pollutants released during coal combustion. Ecotoxicity impacts are higher due to the release of pollutants that adversely affect terrestrial and aquatic ecosystems, leading to biodiversity loss and ecosystem degradation.

The Carbon-Free System exhibits markedly lower impacts across all categories, reinforcing the environmental benefits of eliminating carbonaceous additives. By adopting alternative materials like Moldcote, the system minimizes the release of harmful emissions, thereby protecting human health and preserving ecosystem quality.

The application of the ReCiPe method allows for a detailed assessment of the environmental impacts of the two greensand moulding systems by analyzing the endpoint indicators. The analysis shows that the Carbon-Free System has significant environmental advantages over the Carbon-Based System across multiple impact categories, not just in terms of GWP.

These findings highlight the importance of adopting carbon-free technologies in foundry operations to enhance sustainability. Eliminating carbonaceous additives and optimizing material usage can substantially reduce environmental impacts. Advanced LCA methods like ReCiPe provide valuable insights for decision-makers to develop strategies that lower the environmental footprint of foundry processes.

5 Conclusions

This study provides robust evidence that Carbon-Free Greensand Moulding Systems deliver significant environmental and operational improvements compared to traditional carbon-based systems. The Life Cycle Assessments reveal that Carbon-Free Systems substantially reduce CO_2 emissions, lower the overall environmental impacts on human health, ecosystems, and resource consumption, and enhance energy efficiency across key stages of the casting process. By incorporating sustainable binder technologies and optimizing sand reclamation, these systems offer a viable pathway for the foundry industry to meet stringent sustainability targets, including Net Zero emissions. The findings underscore the critical role of carbon-free technologies in advancing the sustainability of metal casting, highlighting the need for industry-wide adoption to achieve meaningful reductions in environmental footprints.

Future work should investigate the scalability and long-term performance of Carbon-Free Systems in various foundry settings to validate their effectiveness across different conditions. Research should also focus on the economic aspects, including cost-benefit analyses of transitioning to carbon-free technologies. Additionally, exploring advanced materials and additives that further minimize environmental impacts, along with developing industry standards and best practices, will be crucial for broader adoption and achieving sustainability goals in metal casting.

Acknowledgments

The authors thank and acknowledge Foseco International Ltd for their support and contribution to this research.

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2025-03-03
Springer
https://doi.org/10.1007/978-3-031-80676-6_151
Karadimas G, Pagone E, Birch T. (2025) Environmental impact lifecycle assessment of green sand moulding in foundries. In: Light Metals 2025. TMS 2025 154th Annual Meeting & Exhibition, Las Vegas, NV, USA. The Minerals, Metals & Materials Series, pp.1218-1225

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