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# Comparative life cycle assessment of asphalt modified with mineral-based and biomass-derived nano silica

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**Abstract.** Asphalt pavements are prone to issues such as permanent deformation and cracking, which reduce pavement lifespan and increase maintenance costs. As a result, there is a growing demand for asphalt mixtures that offer higher durability and improved performance over time. To meet this need, researchers have explored various modifiers, with nano silica emerging as a promising material due to its ability to enhance the mechanical and structural properties of asphalt binders. Nano silica ($SiO_2$) is one of the most commonly used nano additives due to its ability to improve the mechanical properties of asphalt mixtures. However, nano silica is produced from non-renewable sources, raising concerns about its environmental sustainability. This study compares the environmental impacts of nano silica and rice husk, a renewable agricultural by-product, as asphalt modifiers using Life Cycle Assessment (LCA). The system boundary includes the cradle-to-gate phase, covering raw material production, transport, and asphalt mixing. The results show that rice husk produces lower impacts in several categories, including global warming potential, fossil resource scarcity, and cumulative energy demand. These findings suggest that rice husk can be a more sustainable alternative to nano silica in asphalt modification while maintaining environmental performance.

## 1. Introduction

Asphalt pavements may suffer from persistent deformation and cracking, resulting in reduced longevity and increased maintenance costs [1,2]. Researchers investigating pavement are focused in nanoparticles with silica layers due to their potential to improve the physical, rheological, and engineering properties of bitumen [3]. [4] shown that the addition of nano silica (nano-$SiO_2$) increases the binder's performance to temperature variations. The modified binder exhibited superior resistance to rutting at elevated temperatures and enhanced fatigue performance at moderate temperatures compared to the untreated asphalt binder. Their investigation indicated that asphalt mixtures containing 4% micro silica had the lowest propensity for rutting as temperatures increased. Additional research has demonstrated that including micro silica into asphalt mixtures reduces rut depth compared to a control binder. Moreover, it was determined that the greater the amount of nano silica, the lower the rutting intensity was observed [5,6]. However, despite its beneficial, unrenewable-based nano silica has an added environmental burden if compared to the conventional asphalt binder as well the uncertainty surrounding its environmental disadvantages. For instance, [7] reported that, during the production phase, asphalt mixture modified with nano silica exhibited a global warming potential of $7.44563 \times 10^3$

kg $C_{O2}$-Eq per functional unit (FU), in contrast to the standard asphalt mixture's 7.41900 × $10^3$ kg $C_{O2}$-Eq per functional unit.

To mitigate the environmental pressure caused by the usage of mineral-based nano silica, particularly the issue of mineral resource depletion, numerous researches have explored the potential of biomass-derived nano silica as an alternative additive. In line with this, it becomes increasingly relevant to explore the use of such materials sourced from biomass. Currently, researchers are shifting their focus toward more sustainable raw materials to substitute conventional sources such as sodium silicate and quartz sand. These alternative sources are typically obtained from agricultural waste and processed using precipitation or wet methods to produce nano silica. A wide range of agricultural waste has been studied for this purpose, such as sugarcane bagasse [8], bamboo leaves [9], corn cob [10], rice husks and straws [11], sorghum leaves [12], wheat straws and husks [13]. Among these, rice husk has been one of the most frequently used types in asphalt modification applications [14–18].

Given this development, it becomes important to evaluate and compare the environmental benefits of nano silica modifiers derived from mineral and biomass sources. However, such a comparison has rarely been explored. A life cycle assessment (LCA) method is therefore essential to provide an extensive valuation of the environmental footprint of additive-modified asphalt mixtures across their life cycle. Accordingly, this research is intended to address the existing research gap by comparing the two most prevalent types of Synthetic Amorphous Silica (SAS) used in asphalt mixtures, mineral-based (M-SAS) and biomass-derived (RH-SAS), to offer insight into the corresponding environmental impacts. Thus, the objective of the research is to quantify the environmental footprint of both alternatives by means of the LCA approach based on the ReCiPe 2016 method through SimaPro software. In addition, the study compares the environmental performance of the two types of nano silica, highlights significant differences, and identifies key process stages (hotspots) that contribute most to the overall environmental burden.

## 2. Material

Three asphalt mixtures for asphalt course application are evaluated in this research: a neat asphalt binder and two alternatives modified with nano silica—namely, M-SAS and RH-SAS. M-SAS refers to nano silica synthesised via the wet method using sodium silicate ($Na_2O{\cdot}SiO_2$) as a precursor, which is then reacted with acid to form nano silica. On the other hand, RH-SAS is obtained from rice husk waste and converted into nano silica through a wet hydrothermal treatment. This process involves silica extraction through single acid leaching, resulting in nano silicate compounds. In this study, both nano silica types are added at 4% by binder weight to the asphalt mixtures.

All three asphalt binders in this study are utilised in asphalt concrete–wearing course (AC-WC) mixtures intended for the surface layer of road pavements, as shown in Figure 1. The selection of nano silica-modified binders is particularly justified for this layer, given its critical role in providing surface friction and withstanding mechanical and environmental stressors. A uniform surface thickness of 4 cm is adopted, consistent with the minimum specification for AC-WC layers outlined by [19].

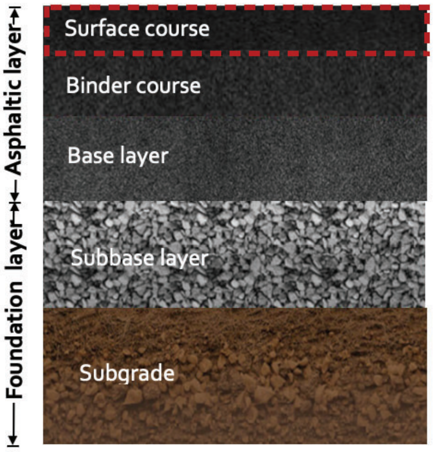


**Figure 1.** Studied asphalt binder in pavement layer structures

## 3. Methodology

### *3.1 Goal and scope*

This study intends to quantify and compare the environmental impact of M-SAS and RH-SAS modified asphalt mixtures during production. The overall impacts are measured, and the associated contributions of each production phase are examined to determine environmental hotspots in the asphalt mixture life cycle.

### *3.1.1 Goal and system boundary*

This study employed a cradle-to-gate framework, encompassing three sequential stages: raw material production, transportation, and asphalt mixing. The complete procedure was elaborated into the subsequent subsystems:

1) Raw materials. The pavement life cycle begins with raw materials extraction, required to produce the asphalt mixture. This comprises aggregates, conventional asphalt binder, and nano silica as an addition. Currently, environmental concerns predominantly occur from quarry operations for aggregate extraction, asphalt binder refining procedures, and the industrial manufacture of nano silica at the manufacturing facility.
2) Transportation. This phase involves raw materials transportation to the Asphalt Mixing Plant (AMP). The environmental impact at this phase results from the consumption of fuel and air pollutants produced by transport vehicles, which are reliant with the volume of products transported, the distance travelled, and the method of transportation employed.
3) Asphalt mixing procedure. Following transportation at the AMP, all raw ingredients are mixed and heated to generate a uniform asphalt mixture. The environmental effects at this stage primarily derive from the thermal energy necessary for heating and the electricity utilised to operate the facility.

### 3.*1.2 Functional unit*

In Life Cycle Assessment, the functional unit is a reference point used to relate all environmental impacts to the intended function of the system. For pavement studies, this should reflect realistic design and usage. In this research, the functional unit is defined as a 1-kilometre road segment, 3.5 meters wide, with a 4-centimetre-thick asphalt layer—representing typical traffic loads and service conditions.

### *3.2 Life cycle inventory*

This section specifies the input and output data sources for the LCA process. The database employed is Ecoinvent version 3.8 [20], evaluated using SimaPro 9.3.3 software. In the raw material phase, the asphalt binder was denoted by the process "Bitumen adhesive compound hot {RoW}| production | Cut-off U." This dataset represents bitumen production at the refinery level, including inputs like thermal energy usage, chemical infrastructure utilised in the manufacturing process, pitch, and related transportation. This phase includes emissions of benzo(a)pyrene, non-methane volatile organic compounds (NMVOCs), and waste handling from decommissioned chemical production sites. The dataset "Gravel crushed {RoW}| production | Cut-off U" represented the production of natural aggregates. This process involves the extraction of raw aggregates from quarries, subsequently followed by mechanical crushing into specified size fractions. It encompasses essential factors such as land use and alteration, energy use from diesel and electricity for machinery operation, material transport through conveyor systems, and related environmental impacts, including air emissions and waste management activities. Additionally, the inventory of SAS materials, encompassing both M-SAS and RH-SAS, is sourced from [21]

In the asphalt mixing stage, the process is modelled using a batch-type asphalt mixing plant with a capacity of 160 tons per hour, requiring approximately 12,000 kWh of thermal energy [22]. Each ton of asphalt mixture was assumed to consume 75 kWh of energy. The thermal energy input was represented by the dataset “Heat, district or industrial, other than natural gas {RoW}| heat production, light fuel oil, at industrial furnace 1MW | Cut-off, U.” It was further assumed that asphalt mixtures incorporating nano silica require 15% more thermal energy than conventional mixtures. Electricity consumption for plant operation was modelled using the dataset “market for electricity, medium voltage {ID} market for | Cut-off, U,” which accounts for both distribution infrastructure and direct atmospheric emissions.

**Table 1.** Transport distance of raw material

| Material | Transport mode | Distance (km) |
|---|---|---|
| Aspal | truk 10-20 ton; empty return | 100 |
| Aggregat | truk 10-20 ton; empty return | 10 |
| M-SAS | Transport, freight, sea, transoceanic, GLO | 3500 |
| | truk 10-12 ton; empty return | 30 |
| RH-SAS | truk 10-12 ton; empty return | 200 |
| PMB MIX | truk 10-20 ton; empty return | 20 |

Transportation distances were first estimated and then refined through direct consultation with industry stakeholders operating within the study region. This phase of the LCA is categorized into four primary transportation flows: the delivery of asphalt binder, aggregates, silica-based additives, and the Polymer Modified Binder (PMB) mixture. Detailed information on the respective distances and transportation modes employed is summarized in Table 1. It is noteworthy that differences in transportation patterns are evident between M-SAS and RH-SAS. The delivery of M-SAS involves two transportation modes, beginning with long-distance sea freight (3,500 km) from mainland China, followed by land transport to the PMB production facility. In contrast, RH-SAS relies solely on land transportation, albeit over an extended distance, as its production is assumed to occur in major rice-producing regions such as Central Java.

## 4. Result and discussion

### *4.1 Cradle to gate impact analysis*

The results of the LCA analysis are presented in Table 2. As shown, the neat asphalt binder exhibits the lowest environmental impacts across all impact categories. This outcome is expected, since a neat binder only consists of two materials, which not only affects the production stage but also simplifies the transportation process and requires lower thermal mixing temperatures. These three aspects contribute to its overall lower impacts.

In contrast, both M-SAS and RH-SAS alternatives show higher environmental impacts across most categories. Interestingly, the results reveal that in some impact categories, M-SAS contributes more significantly, while in others, RH-SAS dominates. For example, RH-SAS has lower impacts than M-SAS in categories such as global warming, marine eutrophication, land use, mineral resource scarcity, and fossil resource scarcity. However, RH-SAS exhibits higher impacts than M-SAS in several other categories, including stratospheric ozone depletion, ionizing radiation, ozone formation (human health and ecosystems), particulate matter formation, acidification (terrestrial), eutrophication (freshwater), ecotoxicity (terrestrial, freshwater, and marine), human toxicity (carcinogenic and non-carcinogenic), and water consumption. This occurrence can be further explained by examining the production methods of each silica alternative.

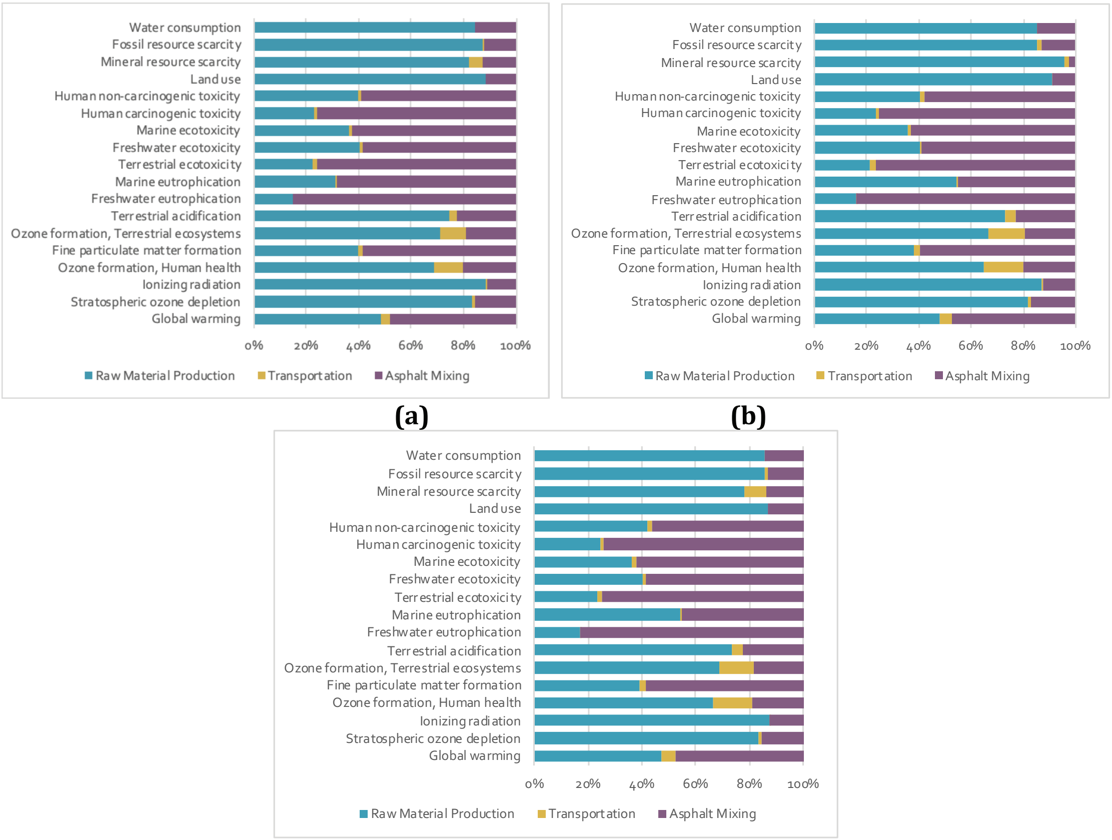
**Table 2.** Environmental impact analysis on studied asphalt binder

| Impact category | Unit | Neat | M-SAS | RH_SAS |
|---|---|---|---|---|
| Global warming | kg CO2 eq | 22,673.00 | 25,303.15 | 25,123.66 |
| Stratospheric ozone depletion | kg CFC11 eq | 0.0220 | 0.0222 | 0.0240 |
| Ionizing radiation | kBq Co-60 eq | 797.59 | 784.66 | 785.57 |
| Ozone formation, Human health | kg NOx eq | 70.03 | 76.81 | 81.12 |
| Fine particulate matter formation | kg PM2.5 eq | 68.03 | 73.97 | 75.01 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 76.21 | 82.88 | 87.18 |
| Terrestrial acidification | kg SO2 eq | 110.04 | 118.88 | 120.93 |
| Freshwater eutrophication | kg P eq | 3.216 | 3.595 | 3.642 |
| Marine eutrophication | kg N eq | 0.259 | 0.434 | 0.431 |
| Terrestrial ecotoxicity | kg 1.4-DCB | 134,719.13 | 146,933.27 | 150,530.93 |
| Freshwater ecotoxicity | kg 1.4-DCB | 120.46 | 132.55 | 132.73 |
| Marine ecotoxicity | kg 1.4-DCB | 230.47 | 253.11 | 255.63 |
| Human carcinogenic toxicity | kg 1.4-DCB | 179.37 | 200.65 | 202.57 |
| Human non-carcinogenic toxicity | kg 1.4-DCB | 4,498.05 | 5,048.92 | 5,206.46 |
| Land use | m2a crop eq | 31.30 | 45.04 | 30.18 |
| Mineral resource scarcity | kg Cu eq | 0.51 | 2.60 | 0.52 |
| Fossil resource scarcity | kg oil eq | 28821.28 | 28,885.11 | 28,809.57 |
| Water consumption | m3 | 22673.00 | 150.70 | 156.94 |

Although RH-SAS is derived from biomass waste, its production involves a hydrothermal process, which tends to result in a higher environmental burden compared to the furnace-based method used in M-SAS. According to [21], the hydrothermal route in RH-SAS relies on sodium hydroxide (NaOH), contributing more significantly to impact categories such as water consumption—due to its aqueous chemical reactions—and ecotoxicity. In contrast, the furnace method applied in M-SAS utilises soda ash ($Na_2CO_3$), which, while contributing more to mineral resource scarcity, shows lower impacts in categories including Terrestrial Acidification Potential, Terrestrial Ecotoxicity, Water Consumption Potential, and Stratospheric Ozone Depletion Potential.

### *4.2 Life cycle stages contribution*

In general, based on the cradle-to-gate life cycle stages—which include material production, transportation, and mixing—the highest environmental contributions are observed in the raw material production and mixing stages (Table 3). In addition, the contribution analysis by life cycle stages shows that the raw material stage remains the dominant contributor to the life cycle impacts across all three asphalt mixtures, as shown in Figure 2. This stage, which includes aggregate processing at the quarry, binder refinery, and additive manufacturing, significantly influences impact categories such as water consumption, mineral and fossil resource scarcity, global warming, and terrestrial acidification.



**(a)** **(b)**

**(c)**

**Figure 2.** Life cycle stages contribution of (a) neat binder; (b) M-SAS; (c) RH-SAS

In general, across most impact categories, the contribution pattern among stages is generally consistent across the three mixtures. However, exceptions are observed in the ozone formation and marine eutrophication impact categories for M-SAS and RH-SAS, which show notable shifts in the proportion of transport and mixing stages (Figure 2b & 2c). In terms of ozone formation (for both terrestrial ecosystems and human health), the contribution from the transport stage increases significantly. This is driven by two factors: the additional transportation requirements for SAS from an external source and the longer travel distances to the PMB blending facility. Conversely, for marine eutrophication, the shares from transport and mixing stages tend to decrease compared to the conventional binder. This shift occurs because the raw material stage becomes more dominant in the SAS and RH-SAS mixtures, reflecting the increased environmental burden associated with the production of silica-based additives. The addition of nano silica additives – whether from mineral source or biomass-based – introduces new environmental load during their raw material production stage which thereby increasing the overall environmental impact.

These findings imply that even though modified asphalt mixtures may demonstrate improved environmental performance in certain impact categories, there are still underlying trade-offs at the stage level, especially driven by how additives are produced and how transport is managed within the life cycle.

### *4.3 Impact analysis*

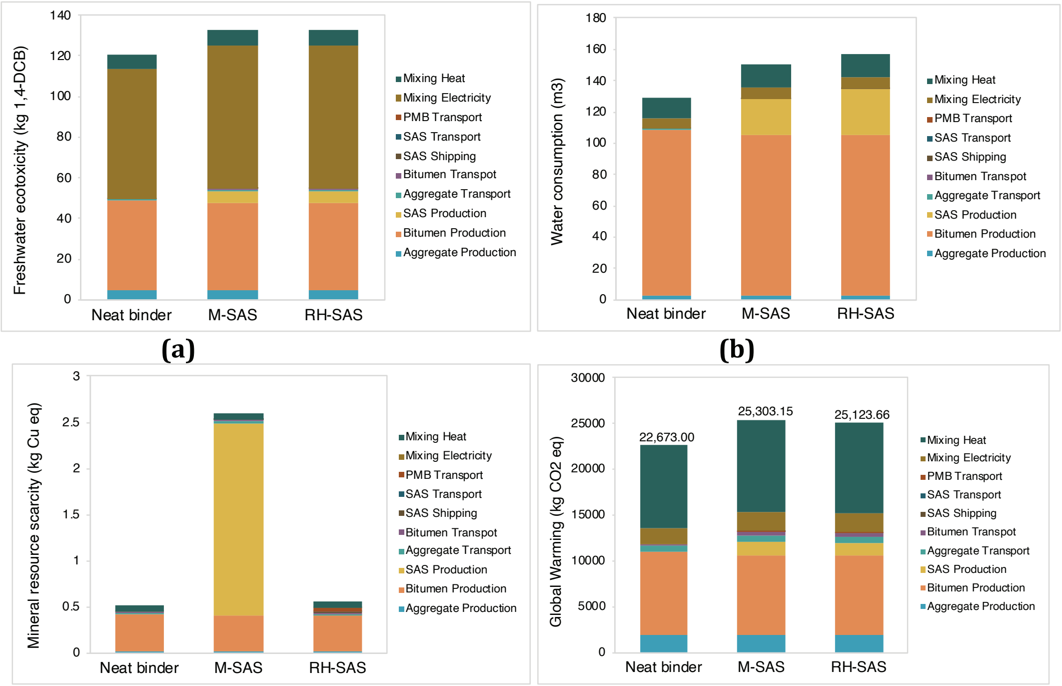
The incorporation of silica into asphalt binder, relative to conventional mixtures, results in notable changes in environmental impact profiles. The addition of nano silica leads to a significant increase in emissions across several impact categories, particularly freshwater ecotoxicity, water consumption, mineral resource scarcity, and global warming [7]. To identify the sources of these changes, a detailed analysis is conducted in this section to track the environmental footprint of each stage while focusing specifically on these four impact categories. Figure 3 shows the process-level contributions to (a) freshwater ecotoxicity, (b) water consumption, (c) mineral resource scarcity, and (d) global warming, across all asphalt mixture scenarios.

For freshwater ecotoxicity, as presented in Figure 3a, the most notable emissions originate from the SAS production stage in both M-SAS and RH-SAS. This is mainly due to the chemical processing steps required to synthesise nano-silica, which involve substances that can potentially affect aquatic ecosystems. It is worth noting that although both types of nano-silica involve additional transport—such as the delivery of raw materials and the extended hauling of PMB to the AMP—their contribution to freshwater ecotoxicity remains relatively small.

A similar trend appears in the water consumption impact category, where SAS production significantly increases water use, particularly for RH-SAS, which results in the highest water consumption overall (Figure 3b). This is because the RH-SAS production uses a wet process, involving stages like washing, filtration, and precipitation, which are water-intensive. As a result, RH-SAS shows the greatest total impact in this category [21].

A different pattern is observed in the mineral resource scarcity category, as shown in Figure 3c, where M-SAS contributes the highest burden. This elevated impact stems from the mineral-based nature of M-SAS production, which inherently depletes non-renewable resources and thus substantially increases the indicator for this category. In contrast, RH-SAS shows a negligible contribution to mineral resource scarcity. This is because RH-SAS is derived from biomass-based materials, specifically rice husk, which are renewable and widely available, resulting in minimal extraction of mineral resources during its production.

For the Global warming impact, a significant increase in total emissions can be observed in both M-SAS and RH-SAS mixtures compared to the conventional one (see Figure 3d). The main contributor to this increase is the nano silica production process, especially for M-SAS, which is based on mineral sources. This production route requires high energy input and extraction processes, thus contributing more $CO_2$ emissions. Among all mixtures, M-SAS shows the highest GWP, not only due to the energy-intensive production process but also because it is derived from non-renewable resources. RH-SAS, although also higher in emissions compared to the control, still shows a lower GWP than M-SAS. This is because RH-SAS is biomass-based (rice husk), which generally has a lower carbon footprint.



(a) (b)

(c) (d)

**Figure 3.** Process-level contributions on impact category: (a) freshwater ecotoxicity (kg 1,4-DCB); (b) water consumption (m3); (c) mineral resource scarcity (kg Cu eq); (d) global warming (kg CO2 eq)

## 5. Conclusion

This study aimed to examine and analyse the environmental burden of asphalt mixture containing mineral-based (M-SAS) with nano silica biomass-based from rice husk (RH-SAS) using the LCA approach in the cradle to gate life cycle. By investigating raw material production, transportation, and the asphalt mixing stage, based on the findings, the following are the major conclusions and recommendations.

- Overall, in most impact categories, raw material production remains the dominant contributor to environmental burdens, followed by the asphalt mixing stage across all mixtures.
- The incorporation of nano silica (both M-SAS and RH-SAS) leads to an increase in environmental impacts across all categories compared to the conventional binder. This increase is primarily attributed to the more complex and energy-intensive production

processes of nano silica, as well as the additional transportation required—first to the PMB facility and subsequently to the mixing plant.

- RH-SAS generates higher environmental burdens in categories related to water consumption and ecotoxicity, mainly driven by the hydrothermal and chemical processes involved in its synthesis.
- M-SAS, on the other hand, results in greater environmental footprints in categories such as mineral resource scarcity and global warming potential, which is mainly due to its reliance on non-renewable mineral sources and the furnace-based production method used.
- Future developments are recommended to prioritise process optimisation for RH-SAS production to reduce its added environmental impact across key impact areas, including human health, ecosystem integrity, and water resource consumption.

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