Sustainable Silica from Rice husk: Techniques, Properties, Industrial Applications and Life Cycle Assessment

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Abstract. Silica [SiO_2] is an essential industrial resource, supporting uses in ceramics, glass, construction, rubber, reinforcement, electronics, coatings and renewable energy technologies. Conventionally, silica is produced with methods like flame pyrolysis or wet precipitation that are highly energy-intensive, depend on non-renewable resources, generate greenhouse gas emissions, chemical by-products and cause mining-related impacts. One sustainable alternative for this is Rice husk which is an abundant Agro waste containing [85 – 97%] of amorphous silica. To check the sustainability of rice husks derived silica as an alternative to conventional silica, it is important to evaluate its environmental performance throughout its life span. One significant method for assessing environmental performance over the life span of materials is through incorporation of Life Cycle Assessment [LCA]. Therefore, the aim of this paper was to evaluate the environmental impacts associated with rice husk derived silica, focusing on factors such as raw material utilization, energy consumption and emissions. The Modelling of LCA for Rice Husk Derived silica was done in accordance with the ISO 14040 LCA Framework using SimaPro Software. The characterization results using the ReCiPe 2016 midpoint method showed that the production of 1 kg of precipitated silica has a contribution of around 4.25 kg CO_2 eq. The LCA results highlight that the production of silica from rice husk presents a great sustainable option to conventional silica, especially from circular economy and waste valorization viewpoints. With the combination of renewable energy sources, green chemistry technologies, and process intensification, environmental performance of rice husk-derived silica can be greatly enhanced to further solidify its position as a sustainable alternative in industries.

Keywords: Rice Husk Silica, LCA, Sustainability

1 Introduction

Silica is one of the widely used inorganic substances at present. Its usage spans to different industries like construction, ceramics, electronics, glass, rubber and other applications like bioremediation, renewable energy technologies. Such wide variety of applications require extraction of silica at a massive scale. The conventional extraction method involves using raw materials like sand or quartz by blasting them at 1400 °C in a furnace [1]. The problem with this is that it leads to excessive virgin material

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extraction, is energy intensive which causes release of GHG emissions. Same is with the production of nano silica, where precursors like sodium tetramethylsilicate, tetraethylsilicate [TEOS], silicon tetrachloride and sodium silicate are used [2]. These precursors are expensive, toxic, huge carbon dioxide emitters and their production is energy intensive too. Because of these reasons, it is necessary to explore alternative materials that are sustainable and cause minimal environmental damage while simultaneously keeping a special focus on circular economy and sustainable development.

Rice Husk, an agricultural waste which has 15-20% of silica content in SiO2 form is one of the promising alternatives [1]. In an agrarian country like India, 120 million tonnes of rice was produced in year 2020-2021 alone. This means that 24 million tonnes of rice husk was obtained which could be burned to produce 4.8 million tonnes of rice husk ash [RHA] [3]. Such enormous amount of waste can be used as a leverage to produce silica sustainably as RHA on burning can have more than 85–95% silica content, depending on the processing conditions [4]. Using this method can help reduce dependency on virgin materials, promote waste recovery, reduce environmental damages and promote national and international circular economy initiatives.

There are different methods for silica extraction from RHA, ranging from direct combustion to precipitation or hydrothermal techniques. For high purity silica, metal impurities are extracted using H_2SO_4 or HCl while in hydrothermal one, high pressure operations are used to decrease chemical consumption [5]. The extraction technique is chosen based on the type of physical properties needed in the final product, depending on surface area, particle size, structure of silica [crystalline or amorphous] etc. [6].

With many benefits being pointed out in incorporating RHS into different industrial products, one must do a critical evaluation of sustainability of RH derived silica to fully understand the environmental impacts of using such type of alternative. Life Cycle Assessment or LCA is one method where the environmental impacts are quantified and categorized into different impact categories. Few LCA studies on RHS, particularly on cradle-to-gate have shown a substantial amount of reduction in carbon footprint when compared to conventionally produced silica [7]. Even with favorable results of quantified environmental impacts, other challenges arise like scaling up, consistency in supply chain, minimizing further impacts related to effluent treatment and energy consumption. This research is also consistent with national priorities in the Bioeconomy and Green Manufacturing roadmap, since agricultural residues like rice husk should be valorized into high-value industrial products, which will help achieve resource efficiency, waste-to-wealth programs, less reliance on mineral sources, and shift to low-carbon manufacturing, which is envisioned in the sustainability and circular economy strategies in India.

In short, RHS can be a suitable example of successful combined effort between waste management and circular economy from industrial perspective. This paper examines the extraction techniques, properties, industrial applications and life cycle analysis of rice husk derived silica contributing towards the sustainability initiatives in the 21st century.

1.1 Techniques

Following is the step-by-step procedure to obtain silica from RH [5].

Pretreatment
RH contains impurities in trace amounts which are in metallic forms like iron, potassium, magnesium, calcium, potassium and manganese. The impurities are removed through alkali or acid pretreatment. Acid pretreatment can be done using chemicals such as H2SO4, HNO3, HCl, H3PO4, CH3COOH. Among these, HCl usage is the best for impurities removal. The acid pretreatment depends on temperature, concentration of the acid and duration of the pretreatment. In alkali pretreatment, KOH, NaOH or Ca [OH]2 can be used. Alkali like NaOH is used to form sodium silicate followed by washing with water separating in solid-liquid stages. Metallic impurities removal is necessary to obtain high silica purity.

Thermochemical conversion
Next is thermochemical conversion of biomass which can be done with or without prior pretreatment process. It uses different approaches like combustion, pyrolysis, liquefaction, gasification, co-firing or hydrothermal electrolysis. In combustion, oxygen is provided which produces energy / heat and further used in steam generation. One kilogram of RH generates somewhere between 13 MJ – 16 MJ of energy. Performing combustion without the pretreatment process would yield 95 wt % of silica with trace amounts of alkali oxides.

Silica
The silica present in rice is amorphous in form. Through pretreatment, it is converted into crystalline form. The crystalline silica is obtained by slow burning of RH at 600 °C while amorphous silica is obtained by burning at 500 °C. Particle size of RH, duration of process, pretreatment conditions and temperature are some factors in determination of properties and structure of RHS.

One common method to obtain silica from RH is through precipitation. It involves taking advantage of the silica content present in RHA. Silica is the major inorganic constituent in RHA as seen through various experiments conducted by scientists over the years. Figure 1 shows the characterization of RHA by weight % [1].

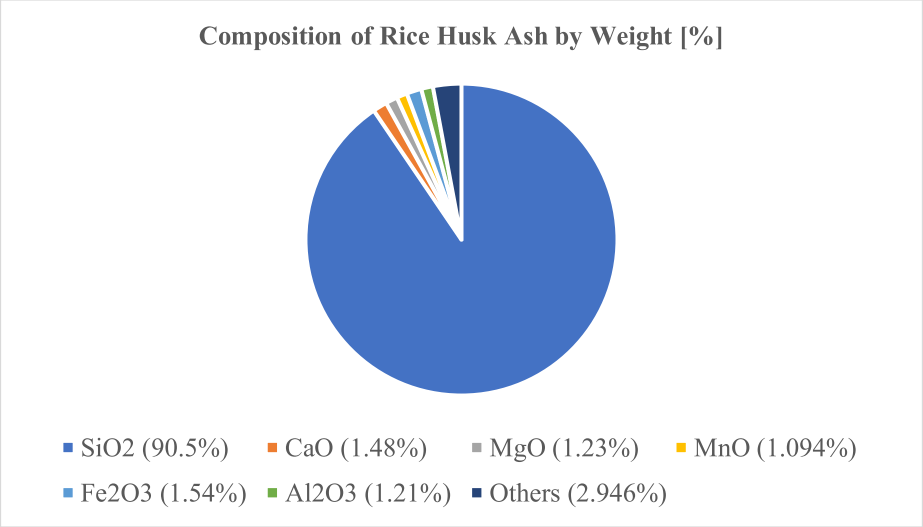


Fig.1. Composition of inorganic constituents in Rice Husk Ash

Through precipitation, the silica present in rich amounts in RHA reacts with alkali like NaOH at temperatures between 180 °C and 200 °C under 6–8 atm pressure to form sodium silicate. The sodium silicate obtained, which is viscous and transparent is then further precipitated by slow and controlled addition of acid at 80–90 °C and atmospheric pressure to form silica. The resultant silica is filtered, washed and dried to make it of high purity. Figure 2 further gives shows the whole process in a flow chart form.

Alkali solubilization:

- $2NaOH + SiO2 \rightarrow Na2SiO3 + H2O$

Acid precipitation:

- $Na2SiO3 + H2SO4 \rightarrow SiO2 + Na2SO4 + H2O$
- $Na2SiO3 + HNO3 \rightarrow SiO2 + Na2NO3 + H2O$
- $Na2SiO3 + 2HCl \rightarrow SiO2 + 2NaCl + H2O$
- $3Na2SiO3 + 2H3PO4 \rightarrow 3SiO2 + 2Na3PO4 + 3H2O$

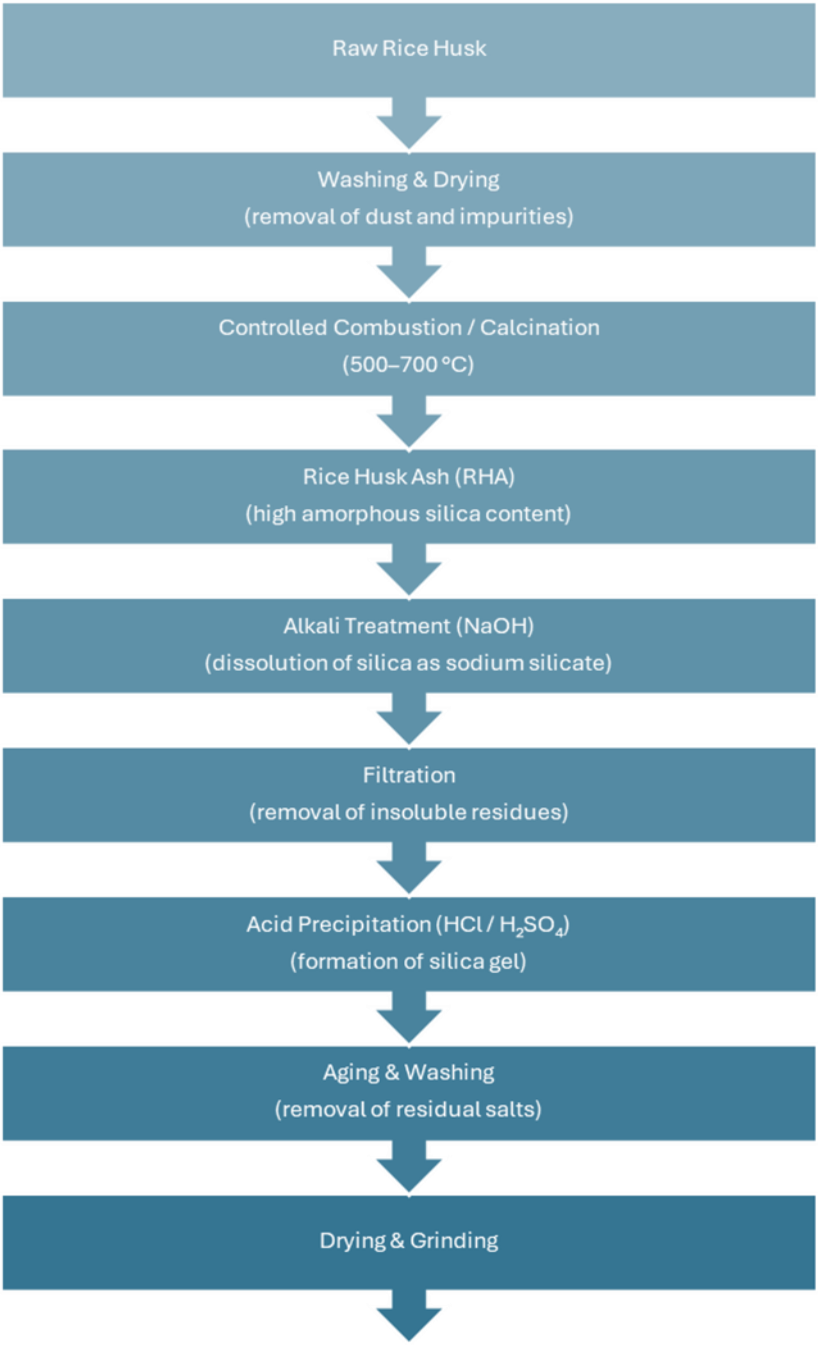


Fig.2. Process Flow Diagram for extraction of Silica from Rice Husk

1.2 Properties

Structure

The structural state of rice husk derived silica depends on the processing temperature. It can exist in either crystalline or amorphous state. For amorphous silica, the processing temperature should be less than 700 °C. Temperatures exceeding 700 °C form silica in crystalline state.

Pore Volume and Surface Area

The processing temperature determines the surface area and pore volume, since the alkali metal oxides present affect the surface melting of silica with changing temperatures. RH incineration at 350 °C and 600 °C shows an increase in the surface area from 60 m2/g to 80 m2/g respectively, whereas between 700°C to 900°C, a sharp drop from 40 to only 1 m2/g is observed.

Particle Size, Morphology and Chemical Species

The silica particles in RHA are cumulations of small nano-range particles. These silica aggregates form fine platelets or globules which can be of varying sizes. The natural form of nanosilica occurring in RH is present in sizes of nano-range, which is less than 100 nm.

Whiteness

Different acid pretreatment processes affect the whiteness of rice husk derived silica. In cases of considerable leaching of alkali metal oxides, especially potassium oxides, the whiteness and brightness increase can be seen [8].

Table 1 gives the comparison of properties of conventionally sourced silica and rice husk derived silica.

Table 1. Comparative Properties of Rice Husk–Derived Silica and Conventionally Sourced Silica

Property	**Rice Husk–Derived Silica [RHS]**	**Conventionally Sourced Silica**
Primary Source	Agricultural waste [rice husk ash]	Mined quartz / silica sand
Silica Content	High [≈ 85–95%]	Very high [≈ 98–99%]
Structural Nature	Predominantly amorphous	Crystalline or amorphous [process-dependent]
Specific Surface Area	Moderate to high [50–300 m^2/g]	Moderate to high [100–400 m^2/g]

Particle Morphology	Irregular, porous particles	More uniform, controlled morphology
Chemical Purity	Slight presence of alkali/trace oxides	High purity, minimal impurities
Reactivity / Pozzolanic Activity	High due to amorphous nature	Lower unless chemically modified
Density	Lower bulk density	Higher bulk density
Thermal Stability	Good up to moderate temperatures	Excellent at high temperatures
Environmental Footprint	Lower [waste-derived, reduced mining]	Higher [energy-intensive mining and processing]

1.3 Industrial Applications

Being a sustainably sourced material, RHS has gained a huge interest and found many applications in variety of industries. Some of them are:

- **Construction Industry:**
  - ⇒ Addition of RHS into the cement improves the concrete properties in terms of durability, strength and resistance to chemical attacks.
  - ⇒ RHA also reduces the clinker content which contributes to carbon dioxide emissions, thus limiting the emissions and in turn minimizing the negative impact on environment.

- **Plastic and Rubber Industries**:
  - ⇒ With hardness and tensile strength better than the conventional material, RHS can be used as a reinforcing filler which enhances the product's resistance to wear and tear and makes it more durable [4].

- **Ceramics:**
  - ⇒ Due to low thermal conductivity of RHS, it can be used in the production of insulation refractories.
  - ⇒ With improved thermal properties and increase in breaking load, it can be used for roofing buildings by partially substituting the clay.
  - ⇒ It can also be used for frit manufacturing to be used in glazes and tiles [9].

- **Some other uses are:**

⇒ As a cleansing agent in toothpaste.
⇒ As adsorbing material.
⇒ As a powder formulation for adhesive substances.
⇒ As anti-caking agent in food industry.
⇒ For blood analysis.
⇒ For dehumidifying air.
⇒ For thermal insulation using silica gel [1].

1.4 LCA

One significant method for assessing environmental performance over the life span of materials is through incorporation of LCA. It helps to gain a detailed understanding of the environmental footprint of processes and products which helps organizations to make informed decisions aimed at minimizing these impacts.

It constitutes a methodology to assess the environmental impacts associated with every stage of a product's life cycle, comprising raw material extraction, manufacturing, use, and ultimate disposal or recycling [10]. LCA has gained wide acceptance in a wide variety of industries.

With more emphasis on Circular Economy, Sustainable development and judicious use of resources, one must explore the alternative sustainable materials that enable recovery of waste and low impact production. Therefore, the aim of this paper is to evaluate the environmental impacts associated with rice husk derived silica, focusing on factors such as raw material utilization, energy consumption and emissions. By assessing these impacts, the study seeks to support evidence-based choices on using more environmentally friendly materials to promote circular economy and sustainable development principles.

2 Methodology

2.1 Process Description to derive RHS

The Process begins with collection of the RH and transporting it to the manufacturing facility. The collected RH is further air dried and burned at controlled temperature to obtain RHA. To make rice husk-derived silica, 2 kg of silica-rich RHA is combined with a sodium hydroxide [NaOH] solution in a mixing tank [HC] to create a slurry. This stage produces a sodium silicate solution by dissolving the silica in the ash, leaving the carbonaceous material intact. Following the slurry's exposure to vacuum filtration [V.F], the wet carbon residue is separated from the sodium silicate solution. Carbon dioxide [CO_2] is bubbled into the sodium silicate solution in a different mixing tank

[HC], where it reacts to produce sodium carbonate solution and silica gel. These Silica gel and Sodium Carbonate solution are further separated by a second vacuum filtration [V.F] stage and then collected separately. The pH is adjusted by neutralizing the silica gel, and any remaining salts and contaminants are then thoroughly cleaned off with water. A second vacuum filtration is performed to get rid of extra water after washing. After drying to eliminate any last traces of moisture, the resultant gel is ground into a fine powder, producing high purity precipitated silica. This method also yields by-products such carbon residue and sodium carbonate solution, which may find its use in other processes, in addition to recovering silica in a form that can be used again. **Figure 3** given below represents the Process flow used to obtain RHS.

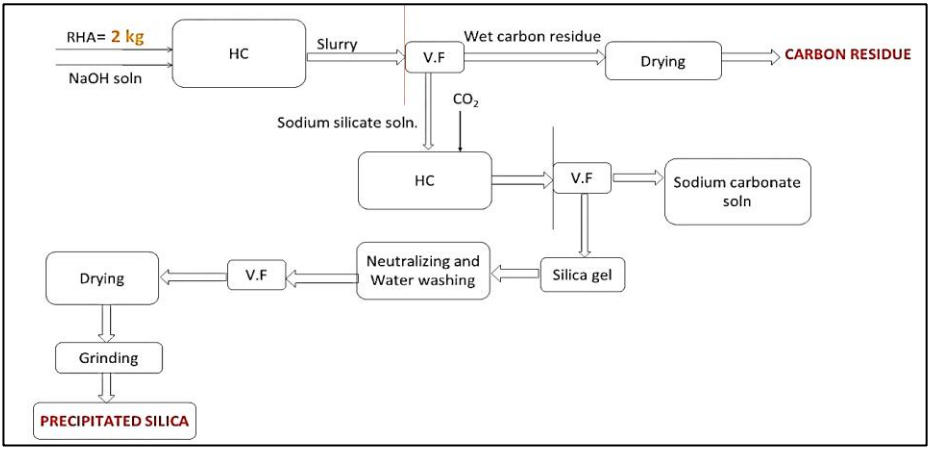


Fig.3. Process Flowchart for Rice Husk Silica

2.2 LCA Methodology

The ISO Standard 14040:2006 [ISO, ISO14040 2006] is followed for modelling of LCA using SimaPro 9.5.0.2 software. The phases of the life cycle assessment [LCA] approach are goal and scope, life cycle inventory, impact assessment techniques, and interpretations. The Figure 4 given below represents the framework used for this LCA methodology.

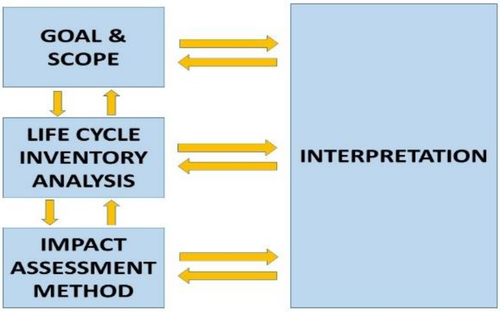


Figure 4: LCA Framework

2.3 Goal and Scope

The aim of the study is to evaluate the environmental impacts associated with the manufacturing of silica derived from RHA. The Scope of the study involves the evaluation of the global warming potential of raw materials used in the production of silica as well as other utilities used for the manufacturing procedure such as electricity, fuel, water & other chemicals. The impacts originating from the transportation of raw materials & other chemicals will also be considered for calculating the Global warming potential. The functional unit considered for this study is **10kg of RH** and system boundary of **Cradle to Gate** will be analyzed in this scope. The Cradle to Gate approach will consider all the stages starting from the transportation of the raw materials to the processing unit, the chemical and thermal extraction procedures and the formation of final product till the factory gate. The System Boundary including all the inputs and outputs is displayed in the **Figure 5** given below.

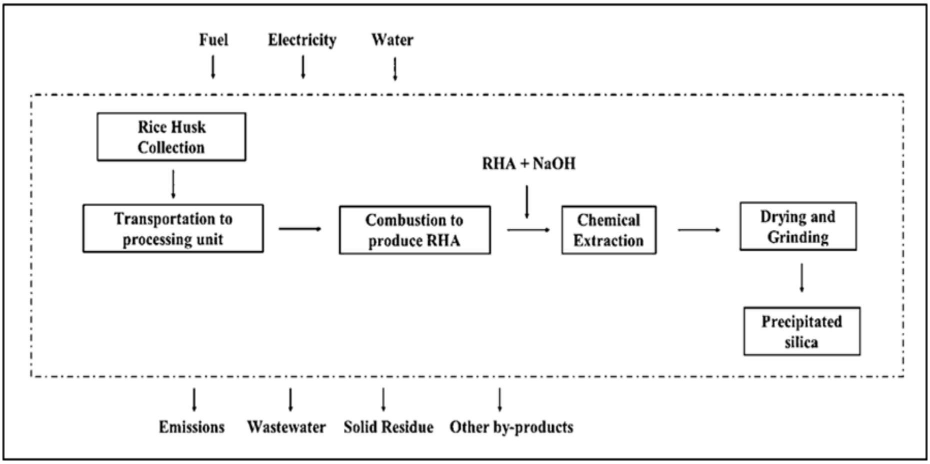


Fig.5. System Boundary to obtain Rice Husk Silica

2.4 Inventory Analysis

The data used for the modelling of LCA of RHS on SimaPro is given in Table 2 below which includes all the input and output materials used during the manufacturing of Silica.

Table 2. Modelling of LCA of Rice Husk Silica

Process 1 : Rice Husk Ash Production			
Input Resources	**Quantity**	**Unit**	
Rice Husk	10	kg	

Transportation [40]km	0.8	tkm	
Electricity burnt for RH	0.277	KWH	
Output Resources	**Quantity**	**Unit**	**Allocation**
Rice Husk	2	kg	9%
Electricity generated [By combustion of rice husk]	41.361	KWH	91%
Process 2: Production of Sodium Silicate			
Input Resources	**Quantity**	**Unit**	
Rice Husk Ash	2	kg	
NaOH Pellets	0.72	kg	
Water	12	kg	
Electricity VF [1]	0.828	KWH	
Electricity Drying Carbon	0.17	KWH	
Output Resources	**Quantity**	**Unit**	**Allocation**
Sodium silicate	13.683	Kg	91%
Carbon residue	0.514	kg	9%
Process 3: Production of Silica Gel			
Input Resources	**Quantity**	**Unit**	
Sodium silicate solution	13.638	kg	
Water	15	kg	
Carbon di oxide	1.13	kg	
Electricity VF [2]	3.787	KWH	
Electricity Precipitation [RXN]	1.242	KWH	
Output Resources	**Quantity**	**Unit**	**Allocation**

Silica Gel	9.2	Kg	45%
Sodium Carbonate Solution	24	kg	55%
Process 4: Production of Precipitated Silica			
Input Resources	**Quantity**	**Unit**	
Silica Gel	9.2	kg	
Water	8	kg	
Electricity VF [3]	0.8	KWH	
Electricity Drying	0.2	KWH	
Electricity Grinding	0.3	KWH	
Output Resources	**Quantity**	**Unit**	**Allocation**
Precipitated Silica	1.486	Kg	100%

2.5 Impact Assessment

The Environmental Impact Assessment was carried out using ReCiPe 2016 Midpoint [I] v1.08 / World [2010] method, which is one of the most popular life cycle impact assessments [LCIA] methods in contemporary LCA modelling studies. ReCiPe 2016 was chosen because it has updated impact characterization, global applicability and can measure various midpoint categories across one framework. In ReCiPe 2016 Framework, the life cycle inventory data is translated into a comprehensive set of midpoint indicators that represents problem-oriented environmental impacts including the potential for global warming, acidification, human toxicity, use of fossil fuels, eutrophication, Eco-toxicity and resource depletion. The ReCiPe method's midpoint indicators are determined using globally averaged characterisation variables that match the World [2010] normalization set, guaranteeing uniformity in impact estimation across various geographical settings. In contrast to previous LCIA methodologies such as TRACI, which were used in comparable research [7], the application of ReCiPe 2016 Midpoint offers a more comprehensive worldwide viewpoint and integrates current characterization elements that align with the most recent scientific consensus. This makes it easier to identify the critical process stages that have the biggest effects on the environment and allows for a more thorough understanding of the possible environmental trade-offs involved in silica extraction from RHA.

3 Results & Discussion

3.1 Interpretation of Characterization Tree for RHS

The life cycle assessment [LCA] that was done on silica from RH focuses on the environmental effect of its production in terms of global warming potential as CO_2 equivalents or CO2 eq. The characterization outcomes using the ReCiPe 2016 midpoint method show that the production of 1 kg of precipitated silica has a contribution of around 4.25 kg CO_2 eq. From different research papers, it is observed that the contribution from conventionally sourced silica is around 31.9 kg CO_2 eq., thus showing that despite RH being a biogas renewable agricultural by-product, the process of conversion to silica remains energy- and resource-intensive. The largest sources of greenhouse gas emissions are the use of electricity by various Indian regional grids, the use of sodium silicate as a mid-stream chemical, and energy consumption for silica gel processing. For example, electricity use alone makes up almost 3.0 kg CO_2 eq, highlighting the influence of grid-specific emission factors since the Indian electricity mix continues to be dominated by fossil fuels. Equally, upstream activities in relation to silica gel [3.15 kg CO_2 eq] and sodium silicate [0.72 kg CO_2 eq] again increase the carbon impact, implying that chemical inputs are comparable to direct energy consumption in dictating environmental impacts. Figure 6 shows the outcomes in the form of characterization tree.

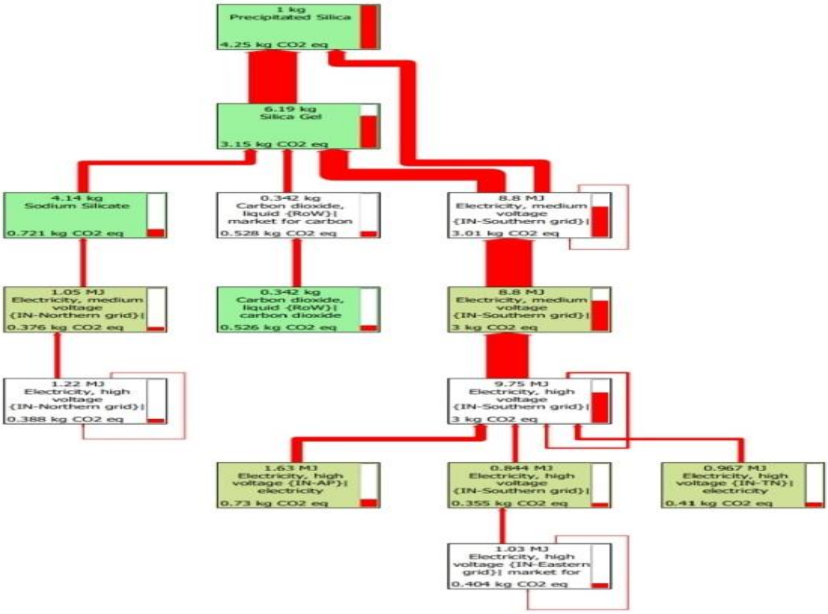


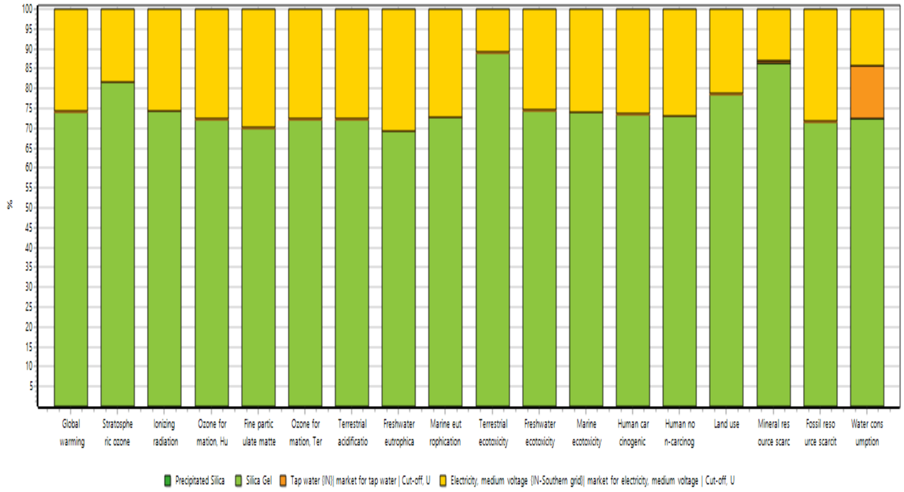
Fig.6. Characterization Tree of RHS through SimaPro

Interpretation of results shows that while the valorization of RH to high-value silica products is a sustainable route over conventional silica from sand mining and energy-hungry thermal processing, the environmental benefits are partly negated by dependence on carbon-intensive electricity and support chemicals. A comparison to conventional silica production routes from quartz implies RHS also retains an advantage in waste valorization and circular economy compatibilities, but optimization is necessary to attain full environmental competitiveness. The most severe impact category seen here is global warming potential or GWP, although it is probably that other midpoint categories like terrestrial acidification and freshwater eutrophication may also display important contributions because of chemical consumption, and this can be investigated in future studies.

From this analysis, techniques for impact reduction can be learned. Initially, switching the energy source for silica processing from grid electricity derived from fossil fuels to renewable energy sources like hydropower, solar, or biomass can drastically lower the carbon footprint, as electricity contributes more than 3 kg CO_2 eq to the total. Second, the 0.72 kg CO_2 equivalent load from this procedure could be reduced by optimizing direct extraction techniques with little chemical use or by using more environmentally friendly substitutes for traditional sodium silicate precursors. Comprehensive efficiency can also be increased through process integration and energy recovery techniques, such as recovering heat generated during RH combustion. Lastly, localised processing near rice cultivation areas may lower emissions associated with transportation and logistics of husk and intermediate products

3.2 Midpoint Impact Assessment

The midpoint impact assessment results for 1 kg of precipitated silica using RHA were obtained using the ReCiPe 2016 Midpoint [H] v1.08 World [2010] characterization method in SimaPro 9.5.0.2 software [11]. The Figure 7 given below shows the results for Impact Assessment that demonstrates the relative environmental burdens across multiple categories, such as Ozone formation, Terrestrial acidification, Global warming potential [Gwp], eutrophication, stratospheric ozone depletion, ecotoxicity, human-toxicity, mineral and fossil resource scarcity, land use and Water consumption. The precipitated silica production phase [shown in green] is the main contributor to the majority of impact categories, making up between 70-85 % of the overall environmental load, according to the stacked bar chart. This is mostly because silica synthesis requires a lot of energy and materials, especially during the precipitation, filtering, and drying phases [12] [13]. Significant amounts of electricity and reagents are used during the production process, which results in emissions related to the creation of CO_2, the release of chemical effluent, and solid waste, all of which together account for the majority of life cycle burdens.



Method: ReCiPe 2016 Midpoint (I) V1.08 / World (2010) I / Characterization
Analyzing 1 kg 'Precipitated Silica';

Fig.7. Impact Assessment result obtained from SimaPro

The tap water market contribution, which is displayed in the Orange Segment of the Stacked bar chart, has a major impact on several categories, such as freshwater ecotoxicity, marine ecotoxicity, eutrophication, and water consumption. These categories are directly affected by wastewater discharge that contains suspended solids and other unreacted compounds, as well as substantial amounts of water used in the washing and purifying procedures [14]. Given the significant contribution of water-related activities, water management strategies are important to enhancing the environment. Implementing closed-loop water systems, recycling initiatives, and wastewater treatment facilities can greatly minimize eutrophication and aquatic toxicity [12]. The environmental efficiency of silica extraction from RHA or other agricultural residues can also be enhanced by adding bio-based or low-impact coagulants during synthesis, which can further reduce hazardous effluents [13].

The energy supply [shown by the yellow segment], which is a representation of the medium-voltage system in Southern India, is a significant contributor to the shortage of minerals, fossil fuels, and the possibility of global warming. The life cycle results have a great influence by the energy input's carbon intensity because the Indian system still heavily depends on fossil fuels, predominantly natural gas and coal [15]. Making the transition to renewable energy sources, such solar or biomass-powered electricity, might greatly mitigate the effects of global warming and the depletion of fossil fuels [17]. Additionally, low-temperature synthesis, heat recovery, and alternate drying methods are process optimization strategies that further decrease energy consumption and enrich sustainability [18]. According to the Overall Midpoint Impact evaluation, auxiliary inputs such as energy and process water also have a significant impact on certain environmental processes, even though the core production process of precipitated silica leads most impact categories. Achieving a more sustainable production pathway requires combining circular water management, renewable energy use and resource-efficient process design. The results suggests that using silica derived from agricultural waste, such RHA, can substantially reduce the environmental impact compared to conventionally produced silica from quartz sand. This is in line with the broader ideas of the circular economy [10]. Future research should integrate endpoint-level impact assessment to transform these midpoint impacts into ecosystem quality and human health outcomes for a more thorough evaluation of sustainable silica systems

4 Conclusion

Producing sustainable silica from rice husks is a promising route for the development of environmentally safe and resource-efficient materials. The Life Cycle Assessment findings show that while the innovation around rice husks significantly reduces dependence on quartz mining and alleviates the exploitation of agricultural waste, the process remains limited by chemicals and energy that cause most carbon emissions. Due to the processing of sodium silicate and energy sourced from fossil fuels, 1 kg of precipitated silica has the potential to produce 4.25 kg CO_2 eq of global warming. However, performance in sustainability can be greatly improved with the application of renewable energy, like solar or biomass energy, process improvements, and chemical selection. Further, closed water systems and combustion heat recovery may optimize resource use. Rice husked silica is superior to conventional silica production methods when considering waste valorization, integration of circular economy, and environmental impact. Therefore, silica produced from rice husks can be considered viable components for sustainable industrial materials, closing the gap between waste management, and materials research and innovation, considering the recent advancements of green chemistry and process intensification in the lab setting.

5 Future Directions

- Integration of renewable energy sources: Inclusion of renewable electrical sources like solar or bio-based energy to perform thermal and chemical processing steps to achieve further reduction of greenhouse gas emissions of the life cycle.
- Process optimization: Chemical usage, reaction conditions, and energy efficiency optimization in the extraction of silica in rice husk to reduce the environmental impact and increase the yield of the material.
- Industrial scale-up: Assessment of techno-economic viability and large-scale human environment at pilot and industrial levels to justify large-scale silica rice husk.

- Broader impact assessment: Life cycle analysis expanded to encompass other impact categories and end-of life scenarios to have a more comprehensive sustainability analysis.

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