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Toward Sustainable Biomanufacturing: A Feasibility Index for Silicon Carbide Production from Rice Waste

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Abstract: Silicon carbide, known for its distinct chemical and physical properties, is increasingly recognized as a critical material in sectors such as energy, space, and defense. Traditional production methods like the Acheson process are energy-intensive and costly, both in terms of investment and maintenance. Additionally, the concentrated nature of its manufacturing can lead to supply bottlenecks, hindering technological progress in key areas. To address these issues, this paper proposes a circular economy approach to silicon carbide production, leveraging the ecological challenge of rice waste disposal to create a new source of silica materials. It includes an evaluation of the economic and technological feasibility of this method and introduces a multidimensional composite index to identify potential early adopters for large-scale implementation. This innovative approach not only reduces reliance on critical minerals but also offers a solution to managing agricultural waste.

Keywords: circular economy; biomanufacturing; silicon carbide; agricultural waste; waste recycling; critical metals; sustainability



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1. Introduction

1.1. Silicon Carbide Properties and Industrial Applications

Silicon carbide (SiC) or carborundum-based materials are polycrystalline compounds used in a wide range of ceramics applications such as electronics, gemstones, thermal management, heating elements, abrasives, and brake liners due to their high decomposition temperature (2830 °C) and oxidation resistance [1].

SiC materials include α -silicon carbide, stable at high temperatures, and β -silicon carbide, metastable at lower temperatures, transforming into α -silicon carbide upon heating [2].

The α phase is harder with better thermal conductivity and stability, suited for high-temperature applications like advanced ceramics and cutting tools, while the β phase, with superior electrical conductivity, is used in semiconductors and optoelectronics [3].

Commercially available SiC advancements led to the commercialization of SiC Schottky barrier diodes (SBDs) in 2001 and power MOSFETs in 2011, enhancing high-frequency power systems [2].

Despite silicon's advantages, its limitations in band-gap energy and thermal conductivity prompted the use of silicon carbide and gallium nitride (GaN) in power semiconductor devices, offering higher blocking voltages, frequencies, and temperatures [4].

Silicon carbide is noted for its high-temperature, high-power, high-frequency, and radiation-hardened applications in power circuit design, marking it as a mature wide band-gap (2.0 eV $\lesssim$ E_g $\lesssim$ 7.0 eV) semiconductor with lower conduction losses and fast switching [5,6]. Wide band-gap semiconductors improve power density, thermal efficiency, and system size, with becoming increasingly vital in industrial settings [7]. However,

in the 1990s, development was hampered by issues in crystal growth and fabrication processes, but these have since been resolved, and today's SiC devices outperform their silicon counterparts in power electronic converters operating at higher temperatures and frequencies [8].

While the benefits and applications of silicon carbide are well-documented, there is an urgent need to develop sustainable methods for its preparation. Current SiC production processes often involve high energy consumption and the use of hazardous chemicals, posing significant environmental concerns. Sustainable approaches can mitigate these impacts, making SiC production more environmentally friendly and reducing its carbon footprint.

Economically, sustainable SiC production methods can lead to substantial cost savings. By reducing energy consumption and minimizing waste, companies can lower operational costs and take advantage of potential government incentives for adopting green technologies. These economic benefits can further drive the widespread adoption of SiC in various industries.

The demand for SiC is rapidly increasing in high-tech sectors, including electronics and renewable energy systems. As these industries grow, a reliable and environmentally friendly supply chain becomes crucial to meet future needs. Implementing sustainable production methods ensures a consistent and responsible supply of SiC, aligning with the industry's evolving standards and consumer expectations.

Regulatory pressures are also mounting. Existing and forthcoming regulations aimed at reducing the carbon footprint of industrial processes make sustainable SiC production not just beneficial but necessary. Companies must adapt to these regulatory requirements to remain compliant and competitive in the global market.

Technological innovation in sustainable SiC production can spur further advancements in SiC applications. Developing cleaner and more efficient production techniques can lead to the creation of higher-quality SiC materials, enhancing the performance and effectiveness of the products in which they are used. This innovation can drive progress across various sectors, contributing to technological advancements and sustainability goals. Integrating these points underscores the importance of sustainable SiC preparation, presenting a compelling case for immediate action in this area.

Table 1 provides a general overview of the most relevant technological applications by each industrial sector and the physical properties of SiC related to specific applications classified by the European Union as strategic [9].

Table 1. SiC technological applications in critical industries and physical properties. Source: Own elaboration.

Critical Industrial Sector	Technological Application	Physical Properties
Aeronautical industry [10]	Ceramic matrix composites for brake disks, turbine bearings, turbine blades, nozzles, heat shields, nose caps, and wing leading edges	High-temperature mechanical properties allow the part to endure the damaging effects of high-speed mechanical friction, high temperature, centrifugal force, and bow shock
Space industry [11]	Ceramics matrix composites as primary materials for the hot structures of launch vehicles	Hypersonic and re-entry vehicles operating in the Earth's atmosphere require low-density, ultra-high temperature resistance, high strength and toughness, and excellent long-term endurance against oxidation and ablation
Space industry [12,13]	SiCSBDs, SiC power MOSFETs, and SiC static induction transistors (SITs) for developing operational SiC motor drives operating in extreme environments	Outer space temperatures and extraterrestrial worlds necessitate ultra-lightweight and resistant power electronics for operating probes, landers, satellites, and spacecraft power converter systems
Renewable energy [14,15]	Efficient inverter circuits for photovoltaic systems	Technical advantages over silicon (Si) to increase switching frequency, enabling reductions in component sizes and leading to reduced system volume and cost, in particular within the 200 V~1200 V range

Table 1. Cont

Critical Industrial Sector	Technological Application	Physical Properties
Nuclear energy [16,17]	Irradiation-hardened materials currently used in fission reactor fuels utilized as structural composites, refractory metals, and ceramics in developing the next generation of reactors	Beneficial properties regarding neutronic behavior and resistance to high temperatures for those desiring higher thermal efficiency in fission and fusion-based nuclear power systems
Semiconductors industry [18]	High-power AlGaIn/GaN high electron mobility transistors (HEMTs) benefit from semi-insulating SiC substrates while semi-conducting (N +) SiC substrates are required for SBDs and MOSFETs	Enhance the performance and efficiency of radio frequency and power-switching devices

Table 1 illustrates the physical properties of SiC MOSFETs which can be transformed into competitive advantages for industrial users and power electronics systems designers.

Figure 1 shows that, as of 2021, the largest importing quotas were held by Germany, Japan, the USA, and South Korea [19].

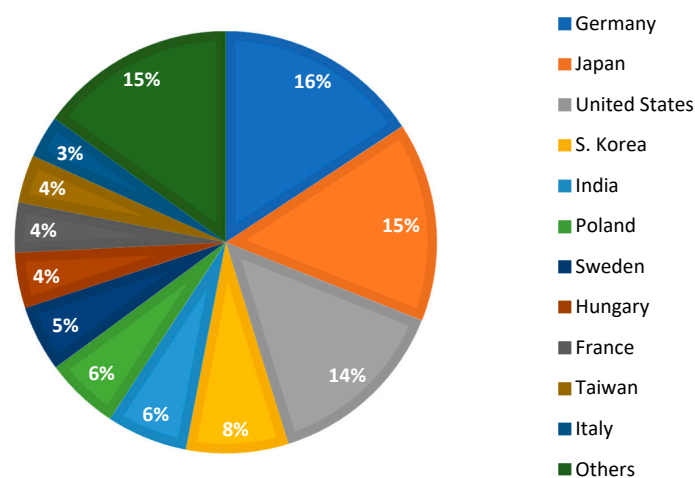


Figure 1. Global import quotas for silicon carbide in 2021. Source: Data elaborated on BACI database HS6 284920 REV. 1992 (1995–2021) [20].

The crucial sub-segment of semiconductors upholding innovation is electronic circuit devices. Specialization in high-tech electronics is used to assess the technological intensity of exports because export performance in electronics, displayed in Figure 2, requires a high degree of technical capabilities associated with high integration into the global economy [21].

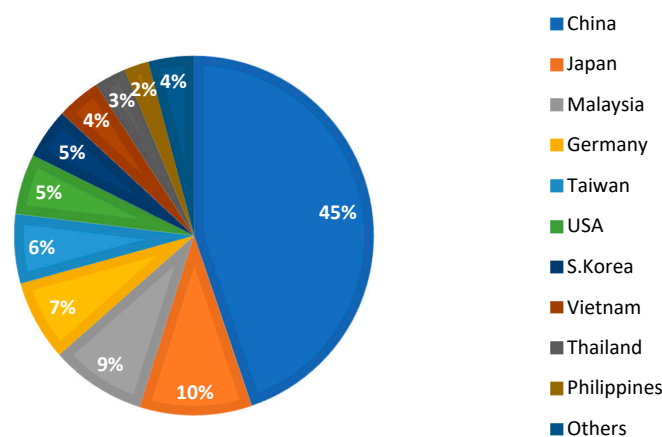


Figure 2. Global export quotas of electronic circuits in 2021. Source: Data elaborated on the BACI database HS6 854213 REV. 1992 (1995–2021) [20].

The relevance of silicon carbide and its composite materials for high-tech applications poses geopolitical risks due to global supply chains, similar to metals and other precious commodities [22]. As the chemical industries continue to innovate and create new materials, importing economies are forced to assess risks and push for substituting rare, concentrated, or polluting elements with more abundant and sustainable ones [23].

1.2. Production Methods: Acheson vs. Biomanufacturing

The first section has assessed that silicon carbide (SiC) is a widely utilized compound in various industries, praised for its high thermal conductivity, extreme hardness, and excellent corrosion resistance. It is manufactured using the Acheson process, named after its inventor who experimented with making diamond-like crystals from carbon and alundum, leading to the design of an efficient electric furnace [24].

The formation of SiC in the Acheson process is a complex phenomenon due to a very high temperature at the center and a relatively lower temperature at the periphery of the furnace, where phase changes, decomposition, vaporization, and condensation occur [25].

Table 2 highlights the key points of the Acheson method for SiC preparation. The preparation of silicon carbide (SiC) via the Acheson method involves several critical steps, including the mixing of silica (SiO₂) and carbon (C), heating the mixture to high temperatures, and finally, cooling the product.

Table 2. Key points of the Acheson method for SiC preparation. Source: Own elaboration based on Kumar, Potturu V., and Govind S. Gupta. “Study of the formation of silicon carbide in the Acheson process”. Steel Research 73, file. 2 (2002): 31–38 [25].

Key Steps	Process Description
Raw Materials Mixing	Silica (SiO ₂) and carbon (C) are mixed in precise proportions as the precursor for SiC synthesis.
High-Temperature Heating	The mixture is heated in an electric resistance furnace to temperatures up to 2500 °C, initiating the SiC formation reaction.
Formation of SiC	At high temperatures, SiO ₂ is reduced by carbon, leading to SiC and carbon monoxide (CO) gas formation [26].
Cooling and Crushing	After the reaction, the furnace cools down, and the SiC is separated, crushed, graded, and processed to achieve the desired purity and size [27].
Purification and Shape Forming	The produced SiC undergoes further purification and is processed into different shapes and sizes for specific applications [28].

Despite its widespread use and efficiency, the Acheson process for producing silicon carbide (SiC) presents significant drawbacks, such as reliance on a heat-resistant furnace and the use of sand and petroleum coke. However, this method incurs high energy consumption, environmental pollution, and considerable startup and operational costs [29], therefore, while the existing infrastructure and expertise in the Acheson process provide some advantages, they are overshadowed by its detrimental environmental impact and substantial energy demands.

As the world grapples with the challenges of climate change and the need for sustainable development, finding innovative and environmentally friendly solutions becomes paramount.

Alternative method of the exploration of bio-sourced materials, specifically rice waste, an abundantly available agricultural by-product.

Rice production generates several types of waste, each with its unique composition and potential uses: rice straw, rice bran, and rice husk.

Rice straw is the stalk left after harvesting rice grains and it is used as animal feed, for composting, or as a raw material for biofuel production, in the production of paper, biochar, and construction materials while rice bran is the layer between the inner white rice grain and the outer hull, rich in nutrients and often used in animal feeds and as a source of rice bran oil, with applications in the food and pharmaceutical industries [30].

The rice production cycle creates massive waste in sheer amounts and kinds of material, including lingo cellulosic feedstock like straw or husk and starchy feedstock like bran and broken rice [30]. However, while the other rice waste streams have useful purposes, only the rice husk, where the silicon bonds to organic material in the outer shell of the rice grain, has the physical properties to form a silicon-carbide skeleton [31].

Rice husk, making up 20–25% of the paddy's weight, is the most valuable yet underutilized by-product, contrasting with bran and broken rice used in food and straw for combustion or feed [32].

East and South Asian economies dominate global rice production, as rice is a staple food in the local nutritional diet. Outside Asia, Brazil, and the USA combined, it contributes only 2.5% to global production, with Italy being Europe's largest rice producer, though in smaller quantities [33]. As an agricultural by-product, rice husks are abundant in rice-producing regions and help reduce pollution by capturing CO₂ and silicic acid from the environment [34]. They consist of about 72–85% lignocellulose and 15–28% silica, particularly around the rice kernel [35,36]. However, due to their low bulk density, disposal in landfills or burning, which turns them to ash, is problematic [37].

Over 90% of rice husks are discarded in open air or water bodies [38], posing environmental risks. Localized waste accumulation and low density hinder long-distance transport [39]. The primary disposal method is using husk biomass in energy via direct combustion into ash or pyrolysis [40].

The second largest use besides energy production is agrifood purposes production for milling or rural lighting [41], with secondary uses in poultry farming, composting, and as a concrete supplement [42], showing improved compressive strength and decreased impact noise [43].

For correctly handling by-products like ash or through pyrolysis, high technical expertise in metallurgy is required, with China, Italy, and Germany leading in these practices (Figure 3).

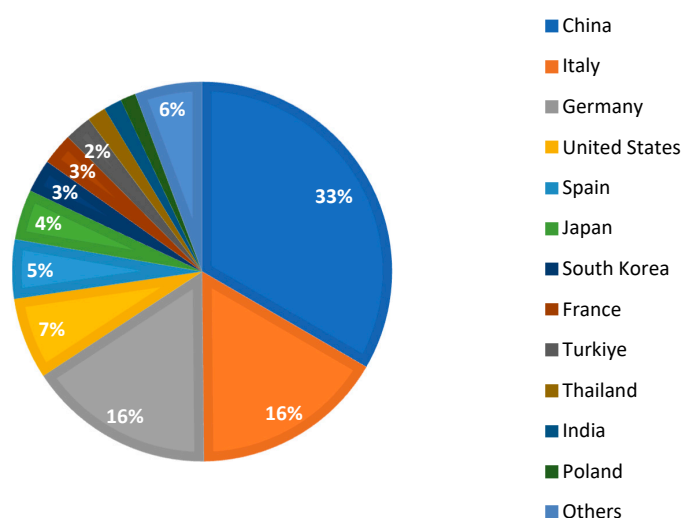


Figure 3. Furnaces and ovens; industrial or laboratory, including incinerators, and non-electric. Source: Data elaborated on the BACI database HS48417 REV. 1992 (1995–2021) [20].

Since the 1980s, developing economies have prioritized finding economically viable uses for rice husks, with the early literature highlighting their potential in producing industrial organic chemicals like silicon carbide, silicate, and insulating materials [44]. Ongoing research has increasingly recognized rice husks as a valuable source of various silicon compounds, including silicon carbide, silica, silicon nitride, silicon tetrachloride, zeolite, and pure silicon [45]. Studies show that rice hulls and husks have a consistent chemical composition across different sources, with low concentrations (10–20 ppm) of aluminum and iron, a crucial trait for reducing major impurities found in raw materials for metallurgical silicon (Ca, K, Mg, Mn) by about 100 ppmw through hot hydrochloric acid leaching [46].

Currently, there is no streamlined industrial process for converting rice husk into silicon carbide, and ongoing refinements are made to the procedure, but all available processes generally include several key steps: separation and pre-treatment of rice husks, thermal conversion or acid treatment, silica extraction, and reduction, and final processing, as shown in Figure 4.

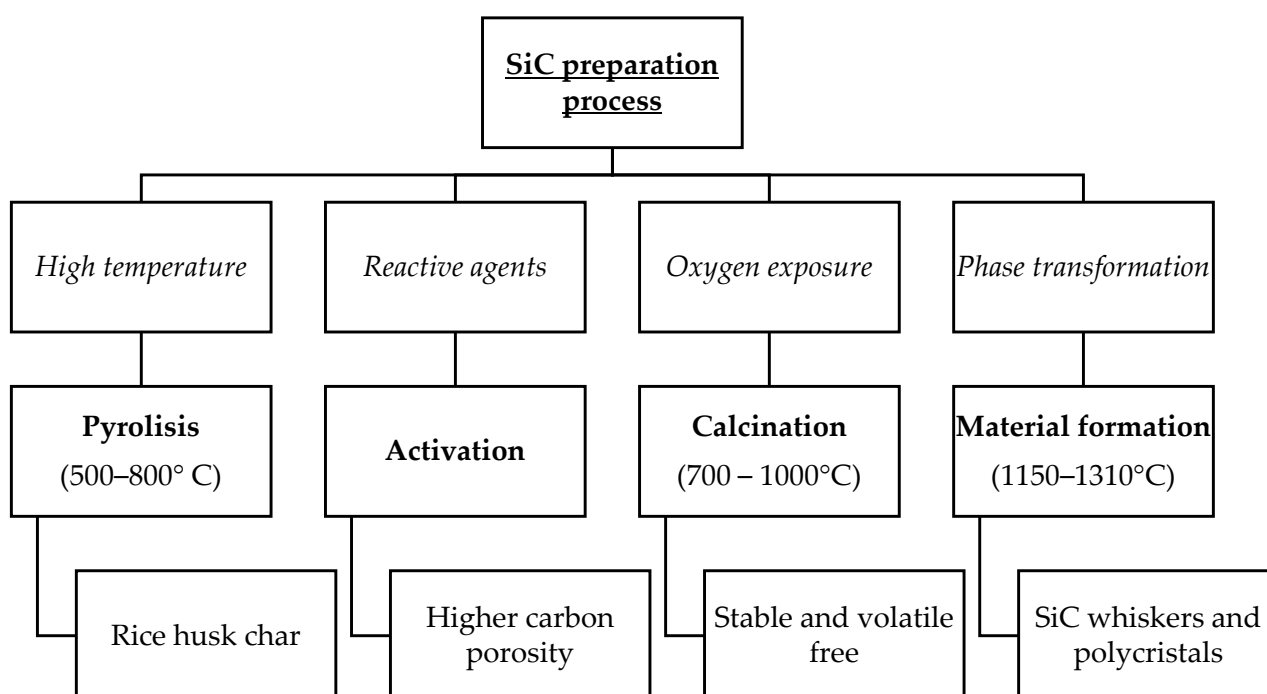


Figure 4. Production process methods and outcomes. Source: own elaboration.

Separation and Pre-treatment of Rice Husks: The process begins by collecting rice husks from milling plants, followed by mechanical separation to remove impurities like dust and soil, ensuring that only pure husks proceed. Pre-treatment methods include sizing, acid or torrefaction washing/leaching [47], alkali treatment [48,49], wet chemical or ionic liquid treatment [35], and bailing or pelletizing. Additionally, biological pre-treatment options have been explored to minimize sugar loss and maximize lignin removal, reducing costs associated with conventional pre-treatments [50].

1. After collection, husks are kept dry and undergo cleaning to remove non-cellulosic materials and achieve the desired moisture content.
2. Conversion into Carbon-Rich Material: The next step involves thermal conversion through pyrolysis, where rice husks are heated in a low or no-oxygen environment, transforming them into amorphous carbon and silica. This phase of the process is critical for the eventual production of silicon carbide.

Pyrolysis, the thermal decomposition of organic components in biomass without oxygen at moderate temperatures, yields tar, char, and gases and has been extensively studied within the scientific community, especially for rice husks over the past few decades [51]. Typically occurring between 500 °C and 800 °C in reactors like rotary kilns or fluidized beds, rice husk poses challenges in gasification and combustion due to its high ash content, which leads to inefficient carbon conversion [32].

During pyrolysis, rice husks transform into rice husk char (RHC), a porous, high-carbon material. At temperatures above 750 °C, amorphous silicon dioxide in the husks converts into cristobalite [52]. A single-stage direct pyrolysis process observes four main transformations: formation of SiC whiskers and polycrystals, crystallization of amorphous silica, and graphitization of carbon. Temperatures between 1150 °C and 1310 °C mainly produce SiC whiskers and crystallized silica, while higher temperatures favor the formation of SiC polycrystals and graphitization. Multistep pyrolysis up to 1310 °C achieves higher yields of SiC whiskers than direct methods [53].

Post-pyrolysis, the char undergoes an activation process to increase porosity and surface area, using activating agents or gases. This is followed by calcination between 700 °C and 1000 °C to stabilize the material and eliminate volatile components.

3. Silica Extraction and Reduction

Rice husk char, a hybrid composite, is transformed into a homogeneous carbon-silica nanocomposite (C/SiO₂) through extraction. During this stage, hydrofluoric acid is used to selectively remove the amorphous silica, leaving behind the carbon structure. The extracted silica is further processed to yield high-purity amorphous silica. Subsequently, a mixture of carbon and purified silica is heated at high temperatures to form the final product [54].

4. Silicon Carbide Processing and Finishing

The final stage involves carbothermal reduction, where amorphous silica is converted into crystalline silicon carbide. This high-temperature process requires the introduction of carbon-rich materials, resulting in the formation of silicon carbide and the release of carbon monoxide. Subsequent steps include milling, crushing, and structural modifications, along with purification, grading, and surface modification to meet quality specifications. The reaction between rice husk silica and carbon, resulting in the formation of β-silicon carbide at 1500 °C, is critical for semiconductor applications. The β-silicon carbide's fine particle size, formed at lower temperatures, prevents its transformation into alpha-silicon carbide [55,56].

Continued research demonstrates that silicon carbide, derived from rice husks, holds significant potential for advanced technologies due to its economic and environmental benefits. Su et al. (2016) developed a scalable process to produce β-phase SiC nanoparticles from rice husks at relatively low temperatures (600 °C), effectively preserving the morphology of biogenetic nano-SiO₂ and offering a cost-effective solution for large-scale production while addressing high energy consumption [57]. Further innovations include employing spark plasma sintering to create SiC ceramics from annealed rice husks, optimizing the distribution of reacting components, and eliminating the need for a separate mixing stage, thus advancing ceramic materials manufacturing [58].

However, the final outcome of these rice husk valorization technologies will be determined by the range of applications to expand their utility beyond traditional uses, not limited to biosilica but also, through thermochemical processes, biofuels with the potential to contribute to sustainable energy solutions [59].

Experimental research has also explored the kinetics of the acid extraction treatment of rice husk such as the research by Liashenko et al. (2020), establishing a methodology to obtain high-purity SiC suitable for various applications, especially in enhancing electrophysical and anti-corrosion properties for extreme scenarios [60]. Moreover, Jaswal and Nandabalan (2022) used rice husk-derived silicon nanoparticles to enhance anodes in microbial fuel cells, significantly boosting power generation and COD removal efficiency, and highlighting the potential of SiC from rice husk [61]. The versatility of rice husk-silica

transformation has been further demonstrated through the synthesis of silica nanoparticles, optimizing conditions for high yield and purity, suitable for environmental applications like water treatment [62]. Additionally, advancements in extracting silicon and carbon from rice husks through molten salt electrolysis have shown potential for producing cost-effective and sustainable lithium-ion battery anodes [63].

The studies presented thus far provide evidence that silicon carbide is an emerging material with plenty of applications in advanced technologies and enormous economic potential, rice husk is an environmental problem better handled by recycling, and the scientific community is working on the technological feasibility of rice husk-SiC transformation with experimental successes.

1.3. Objective of the Study and Research Hypothesis

The study investigates the economic criticality of silicon carbide (SiC) for strategic industries, hypothesizing that due to the high costs and investment required for traditional SiC production, there may be significant concentration and potential chokepoints in the global supply. The primary goal is to thoroughly examine both the strengths and weaknesses of current SiC production technologies and the innovative biomanufacturing of SiC from rice waste.

Most existing research on rice by-product recycling focuses solely on scientific feasibility, lacking an assessment of technical and economic scalability. This study aims to develop a comprehensive feasibility index for localizing SiC production across different geographies using rice waste, evaluating economic incentives, technological readiness, and the role within the global electronics supply chain.

The study also seeks to identify economic incentives to encourage the adoption of SiC biomanufacturing over traditional methods like the Acheson process, assessing supply chain readiness and dependencies. These dependencies are crucial in determining the viability and scalability of adopting a circular economy approach for SiC manufacturing, particularly for economies with significant electronics exports, which may benefit from adopting SiC biomanufacturing due to its growing use in semiconductor technologies.

Finally, the study will couple this feasibility index with a comprehensive assessment of both technologies at their current stages, discussing practical implications for the industry.

2. Materials and Methods

This research uses a mixed method to address the issue of the country's readiness to adopt a sustainable alternative to the traditional silicon carbide manufacturing process. Firstly, the market concentration of silicon carbide export is assessed via a Herfindahl–Hirschman index (HHI). A relevant set of statistical indicators is identified to capture the practicability and the country's readiness. In conclusion, data are weighted in a composite to assess the practicability of adopting this industrial process in the major rice-producing and silicon carbide-importing economies.

Both methodologies are based on the conceptual frameworks utilized in development economics research [64,65], and composite synthetic indicators are vastly utilized by organizations, including the European Commission, specialized United Nations agencies, the World Bank, and the World Economic Forum, to measure the nation's capabilities considering the multifaceted nature of technological change [66].

Figure 5 shows visually the values of the market concentration of the global export quotas for silicon carbide.

The HHI index can then provide a dependable measure to objectively establish if production is too concentrated and suppliers need to diversify their sourcing portfolio [67]. If a high HHI is verified, it emphasizes the need for a sustainable production process when applied to the global silicon carbide market.

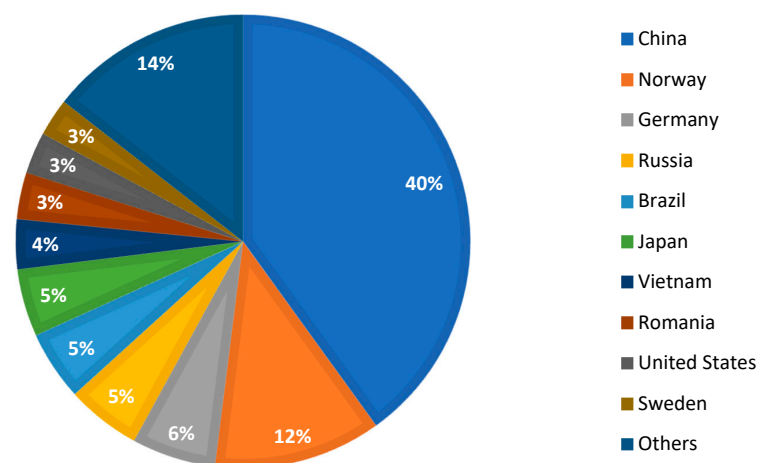


Figure 5. Global export quotas for silicon carbide in 2021. Source: Data elaborated on the BACI database HS6 284920 REV. 1992 (1995–2021) [20].

The HHI is defined as subscript n in the equation:

$$HHI (ex) = \sum n = N \times S_n^2$$

where:

n indicates the trading partner;

N indicates the total number of trading partners;

S_n is the export value share sourced from the n th trading partner.

$$S_n = (s_1, 2, 3 \dots \times 100) / \sum S_n$$

Silicon carbide holds an HHI Index value of 1907 and stands only slightly below the 2000 points threshold valid in the European Union for a concentrated market. However, a single data point is not indicative to fully assess the criticality of its supply, as shown in Figure 6.

We can conclude that although silicon carbide is not one of the most concentrated critical materials, its concentrated supply is susceptible to being disrupted in the case of crisis [68]; therefore, we proceed to a more specific economic assessment of the supply chain: the calculation of the multidimensional composite index for SiC biomanufacturing.

The composite index investigates which economies could benefit from the adoption of this sustainable production process, given the availability of several weighted factors already mentioned in the study: critical high-tech and manufacturing knowledge, rice husk availability, and silicon carbide imports.

Composite indices are considered valuable in representing aggregate measures of a combination of complex phenomena that require multidimensional measures [65].

To identify the country's readiness to implement this technology, the following parameters were weighted with an explanation attached for each one of them:

Rice producer economies: A proxy for the availability of rice husks because the industrial process to be efficient requires low-cost and abundant raw materials. Variable: Annual rice production in tons per country (FAO, 2021) [33].

Electronic circuits' export economies indicate the country's involvement in the electronics industry, a proxy indicator of high-tech capabilities in semiconductor manufacturing, a potential end market for silicon carbide, and a sector requiring highly skilled human capital. Variable: Electronic circuits' export value in US dollars per country (BACI, 2021) [20].

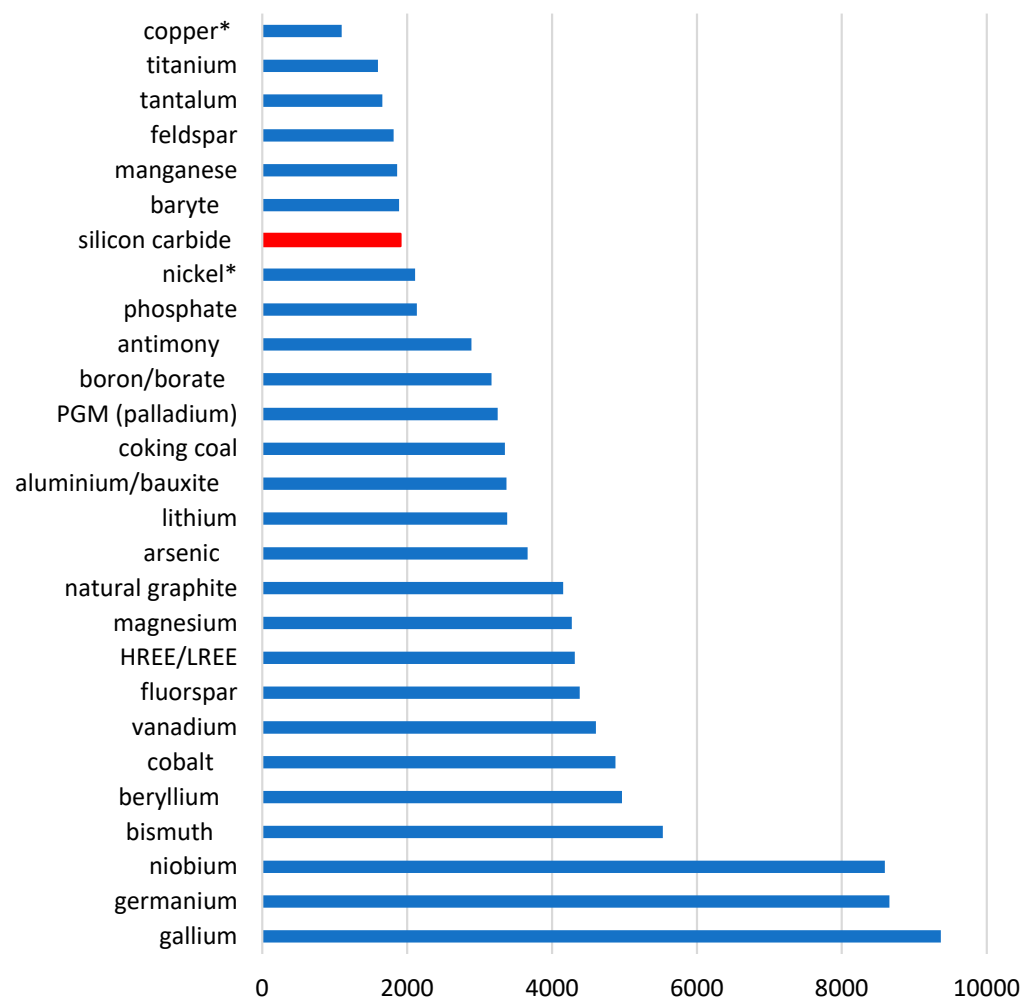


Figure 6. HHI concentration index applied to the EU Critical Raw Materials list for strategic technologies [9]. Note: As silicon carbide, highlighted in red, is not a pure mineral, the HHI index is calculated on export data. Source: BACI, 2021 [20] and World Mining Data 2023 [68] *.

Non-electric industrial furnaces reflect a country's technological competence in handling high-temperature processes, crucial for rice husk thermal conversion, with the export value of these furnaces measured in US dollars (BACI, 2021) [20]. Silicon carbide import economies highlight the need for import substitution, either due to the absence of domestic manufacturing or insufficient national production, with similar data on industrial furnace export values (BACI, 2021) [20]. Comprehensive trade data from the BACI database show bilateral trade flows for 200 economies, covering over 5000 products according to the "Harmonized System" nomenclature (HS6 or HS4) from 1998 to 2021 [69]. Additionally, data on rice production are sourced from the FAOSTAT database [33], reflecting figures up to 2021.

This study focuses on the top 10% of silicon carbide importers and rice-producing economies, generating over 50,000 tons, as these metrics are vital for assessing the feasibility of recycling rice waste and substituting silicon carbide imports. Data normalization on a standard scale is used to remove unit disparities, aiding in the evaluation of economic and technological viability for silicon carbide biomanufacturing from rice waste. A high correlation among these variables could suggest a viable supply chain from rice production to technological capacities in electronics and furnace production. The findings, including a heatmap, are detailed in Table 3 to provide a clearer understanding of the interrelations and dynamics involved.

Table 3. Correlation Matrix for SiC biomanufacturing factors. Source: Own elaboration based on BACI [20] and FAOSTAT data [33].

Correlation	Rice Producers	Electronic Circuit Producers	Industrial Furnace Producers	SiC Importers
Rice producers	-	0.616	0.494	−0.151
Electronic circuit producers	0.616	-	0.812	0.024
Industrial furnace producers	0.494	0.812	-	0.165
SiC importers	−0.151	0.024	0.165	-

The research hypothesis posits that there is an economic incentive to substitute silicon carbide (SiC) imports with alternative solutions. However, the observed correlation between SiC imports and electronic circuit exports is very low ($r = 0.024$), suggesting that SiC importation may not be heavily dependent on electronic circuit export capabilities and could be influenced by other unrelated factors.

The data reveal a strong positive correlation ($r = 0.812$) between the exports of electronic circuits and industrial furnaces, indicating a significant link between a country's capability to produce and export electronic circuits and its ability to export industrial furnaces. This relationship highlights a robust technological and industrial base essential for developing and manufacturing advanced materials like SiC.

Additionally, a moderate positive correlation ($r = 0.494$) shows that economies with higher rice production tend to have higher industrial furnace exports, implying that countries with substantial agricultural outputs could possess or develop the necessary industrial infrastructure for SiC biomanufacturing. This manufacturing requires agricultural by-products and advanced industrial technology.

There is also a moderate to strong positive correlation ($r = 0.616$) between higher rice production and increased electronic circuit exports. Although this could be influenced by other socioeconomic factors, the rising industrial demand for SiC in electronics might support the development of a vertically integrated supply chain.

Considering the high costs associated with the industrial-scale implementation of this technology and the emergent nature of the biomanufacturing SiC supply chain, a composite index was selected as the methodological tool to determine which economies are most feasible for experimental testing and scaling of this technology.

The composite index (CI) is then defined by the formula:

$$CI_{(n)} = \sum I$$

$$I_n = [(X_n \times 100) / \sum X_n] / 100$$

$$CI = (X_1 \times w_1) + (X_2 \times w_2) + (X_3 \times w_3) + (X_4 \times w_4)$$

where:

X_1 indicates the annual rice production in tons per country

X_2 indicates electronic circuit export value in US dollars per country

X_3 indicates industrial furnace export value in US dollars per country

X_4 indicates silicon carbide import value in US dollars per country

$w_{1,2,3,4}$ indicates the respective weight attributed by the authors to each variable $w_1 = 3$; $w_2 = 1$; $w_3 = 2$; $w_4 = 4$

These weights reflect the relative importance or impact of each factor on the potential success and viability of SiC biomanufacturing in a given country. The weight attribution reflects a strategic approach to emphasize both the supply chain (availability of raw materials and technical capabilities) and the market demand for SiC.

- Rice Production ($w_1 = 3$): Rice husks, a by-product of rice farming, are essential for SiC biomanufacturing, turning agricultural waste into valuable SiC using a signifi-

cant amount of biomass. Countries with higher rice production can provide a steady supply of these raw materials, crucial for reducing costs and enhancing the economic viability of the process. The availability of this biomass is critical because it directly affects the cost and continuity of the production process. High rice production ensures a steady and reliable supply of raw materials, which is essential for large-scale industrial operations.

- Value of Electronic Circuits Exported ($w_2 = 1$): This metric reflects a country's capacity in electronics manufacturing, where SiC finds significant applications. However, this factor is given a lower weight because it primarily reflects downstream market demand rather than upstream production capabilities. The electronic circuit export value is an indirect measure of potential market size and not a direct indicator of SiC production capability.
- Value of Industrial Furnaces Exported ($w_3 = 2$): Industrial furnaces are vital for the high-temperature processes required in SiC production. A higher export value indicates advanced manufacturing capabilities and technological readiness, crucial for SiC manufacturing. The ability to export these furnaces suggests a developed industrial sector, equipped with the necessary technology and expertise for SiC production, warranting a moderate weight in the index.
- Value of SiC Imported ($w_4 = 4$): The import value of SiC directly reflects the existing market demand within a country. High import values indicate a strong current or potential market for SiC products, making this factor the most significant in terms of economic feasibility. Establishing local SiC production in countries with high import values can improve trade balances and provide economic incentives for local industries, and the potential return on investment from satisfying local demand through domestic production justifies the highest weight for this variable.

The weighting scheme aims for a holistic view that balances technical feasibility (raw materials and production capabilities) with economic viability (market demand) to identify economies not just with the capacity to produce SiC but with a clear economic incentive to proceed with greenfield projects as the technology is still experimental.

However, this study acknowledges that the defined weights are open to dispute and further validation. The defined values are based on the assumptions and conditions pertinent to this study and judged by the authors; thus, they may not accurately reflect the relative importance of these variables under different circumstances.

Adjustments to these weights may be necessary to better align with the unique environmental, socio-economic, and industrial factors influencing different supply chains. The respective weights assigned to the four variables ($w_1 = 3$; $w_2 = 1$; $w_3 = 2$; $w_4 = 4$) used to derive the composite index (CI) in this study are subject to variability based on the specific characteristics and conditions of different zones.

Table 4 presents the partial composite index results.

Table 4. Partial results by weight of the CI variables. Source: Own elaboration based on statistical data from FAOSTAT [33] and BACI [20].

Country	Rice Production	Electronic Circuits Exported	Industrial Furnaces Exported	SiC Imported
China	0.820	0.448	0.668	0.064
Germany	0.000	0.072	0.318	0.630
India	0.753	0.002	0.031	0.249
Japan	0.041	0.101	0.086	0.612
USA	0.034	0.055	0.139	0.566
Italy	0.006	0.009	0.329	0.131
South Korea	0.020	0.045	0.056	0.313
Poland	0.000	0.001	0.026	0.226
Thailand	0.129	0.028	0.032	0.051
Vietnam	0.169	0.039	0.017	0.011

Figure 7 shows the results of the CI formula: the weighted results per each supply chain and demand factor are displayed over the threshold of 0.001 in each category of the ranking (except for rice production).

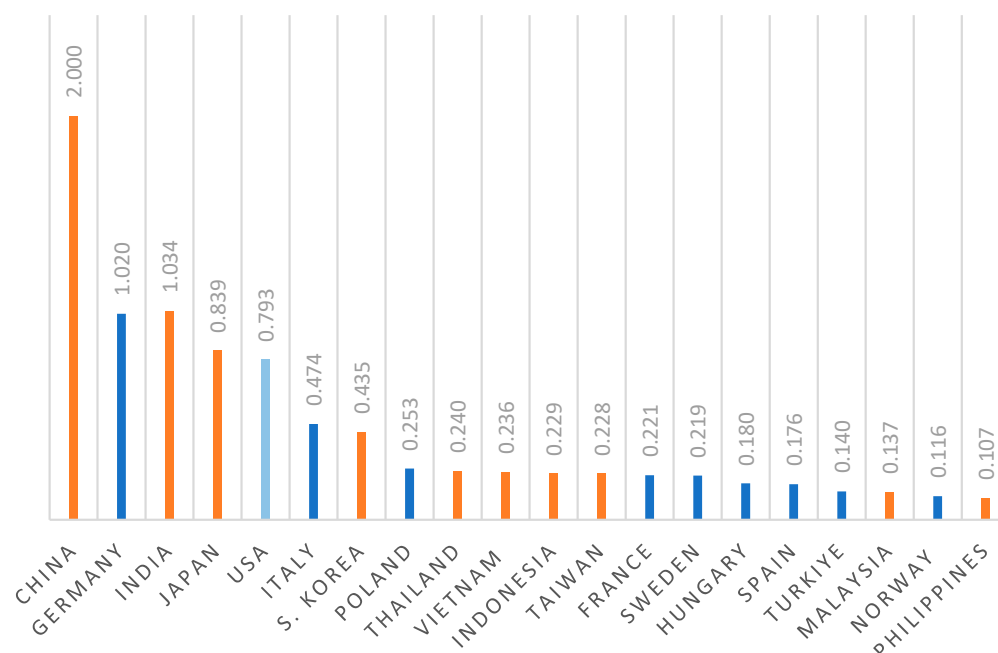


Figure 7. Composite weighted readiness index value. European economies are colored in blue, North American economies are colored in light blue, and East and Southeast Asian nations are colored in orange. Source: Own elaboration based on statistical data from FAOSTAT [33] and BACI [20].

Figure 7 displays the final result of the composite index. It ranges from 0 (lowest readiness) to 2 (highest readiness), indicating economies whose aggregated values surpass a threshold of 0.1. Relevant patterns outlined during quantitative analysis are analyzed in the following section.

3. Discussion and Conclusions

3.1. SWOT Analysis

Over the past two decades, the drive for sustainability alongside advances in material technology has highlighted the circular economy as a potential solution for enhancing supply chain resilience for critical materials like silicon carbide. This study assesses silicon carbide's role in emerging technologies and outlines a sustainable production method using rice husks, demanding specific technical expertise.

The research employs the Herfindahl–Hirschman index (HHI) to verify the high market concentration of silicon carbide, supporting the need for sustainable alternatives to the Acheson method. It also identifies potential early adopter economies by evaluating economic and technological factors, with discussions on the current technology landscape and the bio-manufacturing supply chain for silicon carbide.

Despite the Acheson method's reliability and efficiency in producing high-purity SiC, it is energy intensive, generates significant carbon emissions, and incurs high costs due to the maintenance of heavy industrial equipment [70,71]. Increasing global regulatory pressure for stricter environmental standards could escalate operational costs and drive the shift toward more sustainable technologies, potentially surpassing the Acheson method [72].

The growing demand for SiC in electronics, automotive, and aerospace industries could motivate further scientific research aimed at enhancing efficiency and reducing environmental impacts, aligning with the goal of developing a greener supply chain and maintaining sustainable raw material production. Table 5 provides an in-depth overview of the strengths, weaknesses, opportunities, and threats associated with the Acheson method.

Table 5. SWOT analysis of the Acheson method.

STRENGTHS (S)	WEAKNESSES (W)
Proven efficiency Process scalability Industry acceptance	High energy and environmental impact High investment and operational costs Supply criticality
OPPORTUNITIES (O)	THREATS (T)
Technological improvements Market diversification Rising global demand	Regulatory pressures Alternative technologies Raw materials/energy dependence

Rice husks, plentiful and cost-effective compared to traditional materials like petroleum coke, can be processed into products ranging from pure SiC to construction materials, biomass, and biofuel [73]. This versatility can generate additional revenue and boost rural development in emerging economies by creating jobs and revitalizing local economies through the sustainable reutilization of rice husk by-products [74]. The pyrolysis process, which generates biomass energy, can establish energy self-sufficiency and distribute agricultural profits fairly, providing employment in underdeveloped areas [58].

Alternative solutions to traditional disposal methods like landfilling or burning can turn rice waste into economically valuable products, reducing ecological strain on ecosystems [75]. As semiconductor manufacturing shifts to industrializing economies, moving away from the Acheson method to more sustainable manufacturing could alleviate the health and environmental crises these regions face due to industrial expansion [76]. In developed regions, adopting circular economy principles in industrial food production could mitigate the health and environmental hazards posed by extensive landfill use and massive waste production [77].

Switching from the Acheson method to a process with lower energy and environmental impact could, if technical challenges are surmounted, lead to significant efficiency improvements and cost reductions, creating a cycle of reinvestment and innovation [78]. Additionally, using artificial intelligence could overcome technological hurdles and develop SiC with unique properties for new markets [79]. However, traditional SiC producers' established supply chains and economies of scale could challenge the viability of sustainable alternatives unless incentivized to support the emerging rice husk recycling supply chain [80]. These considerations are detailed in the SWOT analysis in Table 6.

Table 6. SWOT analysis of the SiC biomanufacturing from rice husks.

STRENGTHS (S)	WEAKNESSES (W)
Multi-purpose raw material/process Cost-effective process Lower energy and environmental impact	Scalability challenges Technical challenges Dependence on rice husk price/availability
OPPORTUNITIES (O)	THREATS (T)
Growing demand for end products Incentives for green manufacturing Technological breakthroughs with AI	Industrial inefficiencies Price Competition from traditional SiC producers Uncertain market acceptance

In particular, high-volume raw materials are difficult to handle but there are technical solutions as research suggests that pre-treatment procedures increase energy conversion and burning efficiency, reducing slag formation in the furnaces and grates and diminishing the related expenses of handling, transport, and storage [81].

3.2. Supply Chain Analysis, Correlations, and Production Clusters

Besides the technological and economic aspects of these technologies, data drawn from the composite index clearly indicate that the areas with the highest potential to adopt SiC biomanufacturing are East/Southeast Asia and Europe.

The gravity model in economic theory suggests that trade volume is directly proportional to economic size (measured by GDP) and inversely proportional to distance, geographical or cultural [82]. Therefore, neighboring economies involved in the supply chain could naturally form a regional production cluster. The knowledge dissemination within a cluster would offer the early adopters potential export markets to scale up production and shape the regulatory scenario to favor technological adoption.

In the recent decade, state-led development programs have strived to consolidate the leading role of the Chinese economy in green technologies, which is confirmed by the good performance of China in the readiness index [83].

However, for China, being a consolidated producer of silicon carbide with the traditional process, the adoption of new technologies might face resistance from legacy industrial players, given the potential to disrupt the existing supply chain. On the other hand, implementing a circular approach would be more sensible for high-tech producers and manufacturing economies mostly reliant on silicon carbide imports and concerned by supply chain risks.

The Index shows that the latter group might encompass a potential European cluster mainly focused on the German, Italian, and Polish industrial base, where the demand for silicon carbide, industrial expertise, and the political will to reduce critical dependency is high. The weak correlations between SiC imports and electronic equipment exports imply that although domestic production of SiC and electronics export capabilities may be significant, the dynamics of SiC market demand and supply are not yet related to chip manufacturing.

On the other hand, data show another potential regional cluster in Asia, relying on abundant raw materials and technological expertise, comprising large economies like China, India, Japan, and South Korea, rich in technological and financial capabilities.

The moderate to strong correlations between rice production and technological outputs (electronic circuits and industrial furnaces) imply that these economies could strategically develop silicon carbide biomanufacturing as a way to integrate agricultural and industrial sectors, leveraging existing strengths.

The authors assess that emerging manufacturing economies in South and Southeast Asia, significant exporters of electronic circuits, might benefit the most from the adoption of the SiC bio-manufacturing process as they could enter into the high-value supply chain of SiC-based semiconductors.

A broader assessment of potential global supply chains shows that nations with significant rice production and strong technological sectors could synergistically develop silicon carbide biomanufacturing, integrating agricultural and industrial sectors.

3.3. Methodological Notes and Further Research Possibilities

As a methodological note, it has to be noted that composite indices are inherently dependent on the choice of variables, their compound weight, and data availability. Therefore, while most country rankings using these indicators are generally consistent, sometimes, significant discrepancies for certain nations occur [66].

The ratio behind the authors' choice of prioritizing SiC import value over other factors highlights market demand as the most significant pull factor, given that the material has multiple high-tech applications, while the significant weight for rice production acknowledges the need for abundant and low-cost raw materials to make the process economically feasible.

Lower weights for electronic circuits and industrial furnaces assume not only that the final demand factor generated by SiC-based chips is important for indicating the country's broader technological and industrial landscape but also complementary.

Despite its exploratory nature, this study offers some insight into the impact of this sustainable technology on global and local economies. In future investigations, it might be possible to use different angles, such as the availability of capital, cheap energy, and a skilled workforce, implementing environmental regulations, silicon carbide market scenario evolution, and further technological improvements.

When the technology and the market are more mature, a gravity model analysis on top of the composite index could include variables like market size, distance, and economic integration to analyze the potential of regionally integrated manufacturing clusters, especially within free trade/low barrier economic areas like the EU or ASEAN.

Yet, further research and collaboration are necessary to address technological challenges and optimize production processes. The recent research work of Zharmenov et al. [84] discussed the production of high-strength silicon carbide refractories using silica from rice husk but highlighted the gap between academic research and industrial production and the need for further research to bridge these gaps for practical application.

Nonetheless, the environmental and economic benefits of a circular economy approach via the reduction of resource consumption and, therefore, lower production costs can have high strategic value both at the industry and national level [85].

In conclusion, the current research aims to lay the foundation for future investigations on rice husks' economic and technological viability for the large-scale deployment of silicon carbide biomanufacturing as the adoption and advancement of this industrial transformation have the potential to accelerate progress toward a more sustainable and resilient global economy.

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