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Economic Feasibility Study of Nanosilica Production from Palm Kernel Shell Ash under Compositional and Throughput Uncertainty

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ABSTRACT: This study presents the techno-economic analysis of producing high-purity nanosilica from palm kernel shell (PKS) ash as a potential complementary non-mined silica source. We developed a process model incorporating material and energy balances and assessed economic performance using discounted cash flow analysis with a 10-year plant lifetime and a 22% target internal rate of return (IRR). The study placed particular emphasis on the impact of ash composition and plant throughput variability on overall process economics. In this study, the SiO_2 content in the feedstocks varies significantly (46–65%), directly affecting silica yield, chemical consumption, and utility demand. Consequently, operating expenditure varies significantly across ash sources, with chemical reagents emerging as the dominant cost driver. To some extent, plant capacity analysis showed that increasing throughput improves capital utilization and reduces unit production cost. However, the benefit diminishes at higher capacities, where operating costs become the dominant factor. We also conducted a sensitivity analysis incorporating compositional variability and throughput fluctuations. The results indicated that economic viability is constrained within a specific range of ash quality and throughput. While capacity expansion beyond feedstock-limited conditions can enhance profitability, it introduces supply risks that require careful management.

1. INTRODUCTION

Indonesia is the world's largest palm oil producer, producing around 44-45.5 million tons of palm oil. However, the palm oil industry produces solid waste that accounts for around 35-40% of the total fresh fruit bunches (FFB) processed, including empty bunches, fiber, fruit shells, and burnt ash [1]. Boiler ash fueled by palm fibers and shells still contains 40-60% silica. Extracting it would increase the added value of the ash waste field [2]. To use these materials optimally, new technologies such as nanotechnology are needed. Silica (SiO_2) has been used in various applications, including biomedical fields (such as drug delivery, dental implants, dental blocks, and cosmetics) [3] [4] [5] [6] [7]. These mesoporous silica nanoparticles have high surface area and tunable pore sizes, making them ideal for drug loading and controlled-release applications. Dendritic fibrous silica nanoparticles (DFSN) represent a promising category of mesoporous nanomaterials, particularly in biomedicine. Their unique structural and compositional characteristics support various potential applications, including drug delivery, imaging, and tissue-engineering scaffolds [8].

High-purity nanosilica materials are essential for fabricating semiconductor materials used in advanced electronic devices such as computers and smartphones. The need for high-purity silica is growing as digital technology and artificial intelligence (AI) become more deeply integrated into daily life, driving semiconductor demand [1] (Zhang, 2014; Capgemini Research Institute, 2026). The global market for this material is projected to increase from an estimated USD 1.75 billion in 2025 to USD 3.39 billion by 2034 (Market Report Worlds, 2026).

Countries are racing to invest in semiconductor technology to remain competitive in the AI industry. For instance, Indonesia is mapping its natural resource potential for silica production, particularly quartz sand, as part of its national strategy to participate in the global AI industry (Vietnam News Agency, 2026; Nugraha, 2025). The country possesses abundant quartz sand resources of varying purity levels. However, the high-purity quartz (HPQ) suitable for semiconductors is limited and geographically constrained. Indonesia's highest-quality quartz sand is mostly found in Kalimantan Island, with SiO_2 content up to 99%, while quartz purity in other regions remains low (49-93%) (Prasetyo et al., 2023; Syafrizal et al., 2022).

Globally, HPQ deposits are also geographically concentrated, creating supply vulnerabilities for downstream semiconductor and solar industries (OCDC, 2026; Mohanty et al., 2025; Ullah et al., 2025). Extracting silica from HPQ is inherently challenging because the mineral contains lattice impurities. HPQ purification commonly involves multiple steps, including flotation, magnetic separation, and several cycles of acid leaching (Long et al., 2024). These lengthy purification trains require substantial chemical inputs and high energy, and they also incur yield losses, collectively increasing production costs and limiting supply flexibility (Zhang et al., 2023; Lei et al., 2023; Chen et al., 2024). Removing impurities to produce silica from HPQ often relies on hydrofluoric acid, which poses significant safety and environmental challenges because of its high toxicity and ability to penetrate biological tissue (Li et al., 2023a; Ullah et al., 2025; Li et al., 2023b).

In this context, given Indonesia's abundant oil palm production (Yaro et al., 2022), extracting silica from palm kernel shell (PKS) ash offers a potential complementary route. Unlike quartz minerals, which require extensive purification and beneficiation, PKS ash is already a silica-rich secondary resource generated from oil palm industrial combustion. This thermochemical transformation of PKS may reduce purification steps and overall complexity (Okoroigwe et al., 2011). Additionally, using PKS ash as the silica source provides a non-mined, more sustainable material-sourcing strategy.

The quality of nanosilica used to fabricate electronic parts, such as bipolar transistors and integrated circuits, is far stricter than that required for solar cells. For example, electronic-grade silicon requires an impurity concentration of no more than 1 ppb, whereas the maximum acceptable impurity level in solar-grade silicon is tens of ppm (Gaspari, 2018). Therefore, nanosilica production relies on multiple purification steps to achieve this purity level. Consequently, chemical reagent and utility consumption during purification cycles is the primary cost driver in nanosilica production.

This study evaluates the techno-economic feasibility of producing high-purity silica from PKS ash as a complementary route for advanced electronic and semiconductor applications. The analysis is performed to capture the effect of two layers of uncertainties, namely PKS ash compositional variability and input capacity fluctuations, on process economics. Variations in ash composition directly influence silica yield, chemical demand, and utility consumption, whereas input capacity affects production throughput, equipment utilization, and overall process economic performance (Rodriguez-Otero et al., 2024). This study assesses economic performance under variations in composition and feedstock using two key indicators: the minimum selling price (MSP) and the internal rate of return (IRR). The results may help PKS ash-derived nanosilica plant developers and investors evaluate operational strategies and manage economic risks associated with compositional and input variability (Ullah et al., 2025).

In this study, we implemented a techno-economic assessment framework for the silica extraction process described in the literature, incorporating cost estimation and uncertainty analysis. The results show how compositional and input variability affects economic performance and further define the feasible operating and profitability envelopes under dual-uncertainty conditions. Finally, the study summarizes the key findings, highlights the strategic implications of PKS ash as a complementary high-purity silica resource, and outlines directions for process optimization and scale-up.

2. MATERIALS AND METHODS

2.1 Materials

The raw materials for silica production in the techno-economic analysis were palm kernel shell (PKS) ashes, byproducts of boiler combustion in an oil palm mill. Three oil palm mill companies in Indonesia graciously provided the ashes: PT. Kalirejo Plantation (Kalirejo), PT. Adolina (Adolina), and PT. Eastern Sumatera Indonesia (BM).

2.1. Methodology

2.1.1. Process Description

Fig. 1 schematically depicts the steps to produce nanosilica from PKS ash. The main process consists of HCl treatment to remove metal impurities, followed by calcination integrated with sodium silicate production, subsequent water leaching to dissolve the silica, and final neutralization with sulfuric acid to recover the silica. The main and supporting processes are described below.

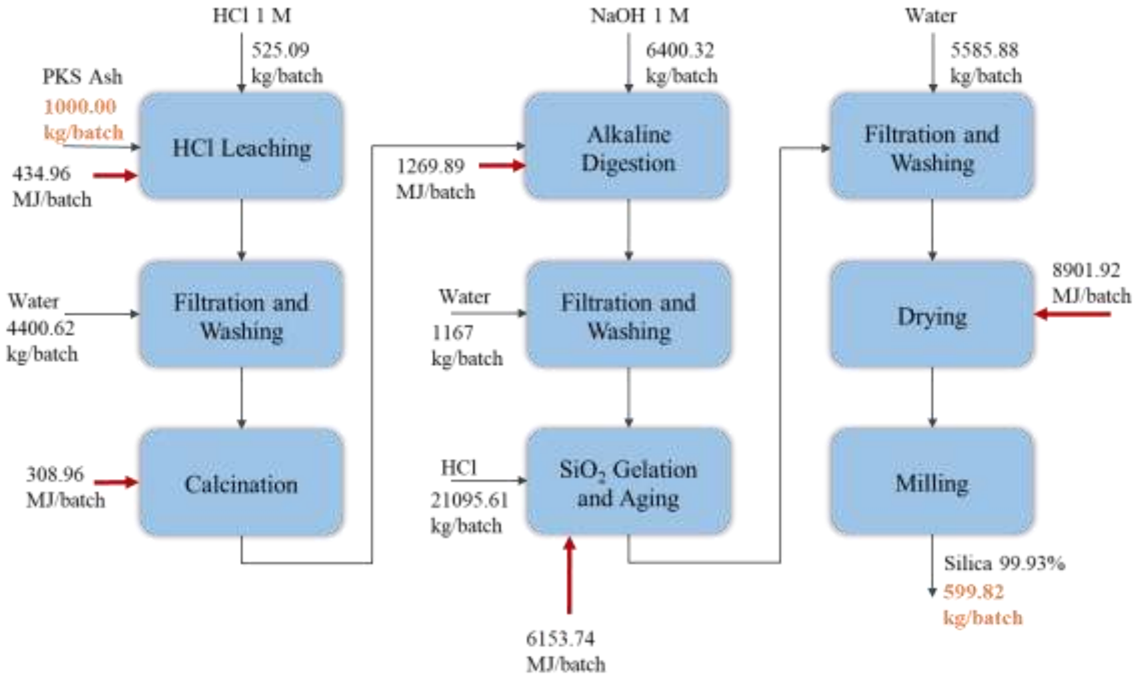

Figure 1. Batch material and energy flow distribution for silica production from PKS ash under the base-case scenario

3.1.1 HCl Treatment for Metal Removal

The first step in extracting silica from PKS boiler ash is removing metal impurities through hydrochloric acid leaching. The process dissolves metal oxides bound within the metal-silica complex by reacting them with hydrochloric acid to form water-soluble salts. A previous study on silica production from rice husks showed that acid leaching can increase silica purity to 96.44% and achieve a surface area of 400.69 m²/g (Ijaz et al., 2025). The chemical reactions of this process are presented as follows:

$$2K_2O + HCl \rightarrow 2KCl + H_2O \quad (1)$$

$$CaO + 2HCl \rightarrow CaCl_2 + H_2O \quad (2)$$

$$Fe_2O_3 + 6HCl \rightarrow 2FeCl_3 + 3H_2O \quad (3)$$

$$Al_2O_3 + 6HCl \rightarrow 2AlCl_3 + 3H_2O \quad (4)$$

$$MgO + 2HCl \rightarrow MgCl_2 + H_2O \quad (5)$$

Metal components differ in their susceptibility to HCl dissolution. K, Ca, and Mg leach to a relatively high degree even at low acid concentrations. The extraction ratio of K with 1.0 M HCl is 73%, as reported by Mananda et al. (2021). In a study using 0.1 M HNO_3, Ca and Mg leaching percentages were 91% and 85%, respectively (Ohki et al., 2004). Fe, however, requires a higher acid concentration to achieve a considerably high conversion. Cui et al. reported that leaching iron (III) oxide with 6 M HCl at 90 °C for 120 min resulted in >99% Fe dissolution. Aluminum, on the other hand, shows the lowest susceptibility to acid leaching. Under the same conditions, the percent dissolution was only 63.19% (Cui et al., 2015). Metal leaching from ash is influenced primarily by acidity rather than by the type of mineral acid used (Ohki et al., 2004). This is also supported by a previous study, which concludes that pH is one of the most important parameters controlling the dissolution of elements from the solid phase into solution (Komonweeraket et al., 2015). Metals tend to form insoluble hydroxides at higher pH, which is contrary to the aim of the leaching process (Jarnerud and J, 2021). When CaO reacts with HCl, it first forms $Ca(OH)_2$, as evidenced by an increase in pH (Gitari et al., 2008). Although it is eventually converted to chloride salts, H^+ ions are already consumed by metal oxides, which have a greater impact on lowering the acidity level. Therefore, controlling the pH during leaching is crucial for increasing Al dissolution.

In this study, the leaching process is modeled using a continuous stirred-tank reactor (CSTR) equipped with pH control to maintain a pH of 3. Initially, hydrochloric acid is fed to the reactor at 10% excess of the stoichiometric requirement to ensure the complete dissolution of metal oxides. Then, add additional volume as needed. The leaching process is performed with 6.0 M HCl at 90 °C for 120 min. For mass balance purposes, the leaching efficiencies of K, Ca, and Mg are assumed to be 100%, considering that these metals are readily dissolved in a strong acidic condition, where removal efficiencies of >90–98% have been widely reported (Ong et al., 2026; Ullah et al., 2025). However, the same assumption does not apply to Fe and Al. The leaching efficiencies for Fe and Al used in the calculation are 99 and 63.19%, respectively.

The leached PKS ash then undergoes three cycles of washing and filtration in a filter press to flush the acid and the soluble chloride salts. The resulting solids, which consist of SiO_2, the remaining metal oxides, and other impurities, are then transferred to a furnace for the calcination process.

3.1.2 Calcination

After leaching, the ash is calcined at 450°C for 1 h to remove residual hydrocarbons and volatile matter, thereby enhancing silica purity and thermal stability. Heating at a controlled rate (e.g., 10°C/min) progressively reduces carbon content and increases specific surface area (Cordeiro et al., 2009). As the organic fraction thermally decomposes and volatilizes, voids form, leading to a more porous silica framework (Nzereogu et al., 2026). The sequence of processes plays a critical role. The recent study reported that calcination after acid leaching yields higher-purity silica with superior catalyst performance. Removing metal impurities prior to heat treatment helps prevent their incorporation into the silica matrix. In reverse sequence, calcining the ash before leaching may encapsulate metal species within the silica structure, reducing their accessibility to acid dissolution (Assawagetmanee et al., 2026).

3.1.3 Sodium Silicate Production

After calcination, the silica remains solid and is mixed with other residual impurities. Recovering silica requires a process that converts it into water-soluble silicate species. This can be achieved by treating the calcined ash with a 1 N sodium hydroxide (NaOH) solution under constant stirring at 80°C for 1 h to produce a sodium silicate solution (Na_2SiO_3), as described by Eq. 6. This process is also commonly referred to as alkaline digestion (Cordeiro et al., 2009).

$$SiO_2 + 2NaOH \rightarrow Na_2SiO_3 + H_2O \quad (6)$$

After the digestion process is complete, the resulting solution is allowed to cool to ambient temperature. The sodium silicate solution is then washed and filtered to remove any undigested ash particles. In this study, we assume a conversion of SiO_2 to Na_2SiO_3 of 93.55%, based on the recovery reported by Costa et al. under identical extraction conditions (Costa, 2018).

3.1.4 Silica Gelation and Aging

The clear filtrate containing sodium silicate was then gelled with hydrochloric acid to form silica gels, as described in Eq. 7.

$$Na_2SiO_3 + 2HCl \rightarrow SiO_2 + 2NaCl + H_2O \quad (7)$$

This hydrolysis step is crucial, as it governs the development of the silica network. The reaction conditions must be controlled, as both gelation kinetics and silica properties are pH-dependent. Liou et al. report that at pH < 3, gelation was negligible, whereas at pH > 8, the resulting gel was unstable (Liou, 2011). According to the study, the optimum pH for maximum silica yield is 7. However, the highest silica purity (99.48%) was obtained at pH = 3. The type of acid used also affects the resulting silica purity. Among the tested acids, namely HCl, H_2SO_4, oxalic acid, and citric acid, HCl consistently produces silica with higher purity and yield compared with the others. Based on these findings, this study assumes silica gelation is carried out using HCl, which is added dropwise to maintain the solution pH at 3. The gelation is subsequently followed by aging at 50°C for 12 h in the same reactor. The mixture of SiO_2 gel and residual solutions is subsequently separated in a filter press. The recovered solids are then dried at 400°C and milled in a ball mill to obtain fine silica powder.

3.2 Economic analysis

Table 1 presents the economic parameters and assumptions used in this study. A plant lifetime of 10 years and a target IRR of 22% were assumed to reflect the risk profile of silica production from PKS ash. Capacity utilization was set at 75% during the first year to account for commissioning. A cost of capital of 8% and a corporate tax rate of 22% were applied, with depreciation calculated using the straight-line method. The process operates in batch mode for 32 hr per batch, yielding 226 batches per year. We included a working capital requirement of 15% of annual operating expenditure to account for variability in feedstock composition and inputs.

Table 1. Parameters for Economic Performance Evaluation

Parameter	Value	Description
Plant lifetime	10 years	Project evaluation period
Base year for costing	2025	All costs normalized to this year
Target internal rate of return (IRR)	22%	Investment performance benchmark
EPC and startup duration	13 months	Engineering, procurement, construction, and commissioning period
Corporate tax rate	22%	Based on prevailing national regulation
Depreciation method	Straight-line	Uniform depreciation over plant lifetime
Capacity utilization (Year 1)	75%	Ramp-up phase during initial operation
Cost of capital	8%	Assumed weighted average cost of capital (WACC)
Operating mode	226 batches/year	Number of production cycles per year
Working capital	15% of annual OPEX	Estimated buffer for operational variability

The techno-economic analysis estimated capital and operating costs based on material and energy balances. Equipment purchase costs were estimated using a method adopted from established chemical engineering design methodologies (Towler and Sinnott, 2022). The total installed cost was then estimated using the Lang factor method for fluid-solid processing, which accounts for installation, piping, instrumentation, electrical systems, and indirect costs. We calculated annual operating expenditure by multiplying chemical and utility consumption by their respective unit prices. We estimated labor as a fraction of fixed capital investment, a simplified approximation suitable for early-stage techno-economic analysis. We estimated working capital as 15% of annual OPEX and included it in the initial investment. We evaluated economic performance using net present value (NPV) with the following equation (Dao et al., 2024).

$$NPV = -I_0 + \sum_{t=1}^{N} \frac{CFA_t}{(1+r)^t} + \frac{SV_N}{(1+r)^N} \quad (8)$$

Where I_0 represents the total capital investment (TCI) of the silica production plant, CFA_t is the annual cash flow in year t, r is the discount rate (cost of capital), and N is the plant lifetime. SV_N is the salvage value of the plant, which was assumed to be negligible at the end of plant life and therefore omitted from the equation. The annual cash flow is calculated as;

$$CFA_t = (TR_t - TC_t - DEP_t)(1 - T) + DEP_t \quad (9)$$

where TR_t is the total annual revenue from silica sales, TC_t is the total annual operating cost including chemicals, utilities, labor, and maintenance, DEP_t is the annual depreciation calculated using the straight-line method, and T is the corporate tax rate.
We also used internal rate of return (IRR) and minimum selling price (MSP) as evaluation parameters. We defined the MSP as the product price required to achieve a target IRR of 22% over a 10-year plant lifetime. A scenario-based sensitivity analysis assessed the impact of variability in PKS ash composition and fluctuations in plant capacity on economic feasibility.

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3.3 Sensitivity Analysis

A scenario-based sensitivity and uncertainty analysis evaluated the impact of fluctuations in PKS ash composition and input supply on economic performance. Feedstock variations, such as biomass-derived systems, and uncertainty in material flows can significantly influence economic outcomes. A sensitivity study can help identify key components that significantly impact overall plant profit (Getu et al., 2013).

The analysis is focused on two primary variables: (i) SiO_2 content in PKS ash, representing compositional variability across different sources, and (ii) plant throughput, representing plant capacity fluctuations. We varied the compositions using actual PKS ash sourced from the oil palm industries mentioned in Section 2.

Palm oil mills' boiler capacity constrained PKS ash throughput variations. Typically, palm oil mills with a capacity of 10–60 tons of fresh fruit bunches per hour are estimated to generate 6–12 tons of solid biomass waste (Rosyidi et al., 2022). This corresponds to producing 65–394 kg of ash per hour. Assuming 10 hours/day and 330 days/year of boiler operation, the annual availability of ash feedstock ranges from 1300 to 215 tons/year. Given a total silica production frequency of 226 batches/year, the feasible processing capacity ranges from 950 to 5753 kg of ash per batch. However, we extended the throughput range to 1000-7000 kg/batch to evaluate its effect on MSP and IRR more comprehensively.

For each ash composition and throughput scenario, we calculated key economic indicators, including operating expenditure (OPEX), minimum selling price (MSP), and internal rate of return (IRR). This approach enables identification of feasible operating regions and construction of a profitability envelope under combined uncertainty.

3. RESULTS AND DISCUSSION

Table 2 summarizes the chemical composition of palm kernel shell (PKS) ash from different sources. It compares five PKS ash types (Kalirejo, Adolina I, Adolina II, BM I, and BM II). SiO_2 dominates all samples, ranging from 46% to 65%.

Table 2. Chemical composition of five different PKS ash sources

Component	Kalirejo	Adolina I	Adolina II	BM I	BM II
SiO_2	61.11%	60.19%	65.18%	46.27%	60.10%
CaO	11.61%	10.50%	6.64%	11.56%	8.68%
K_2O	6.48%	9.83%	8.24%	13.72%	12.62%
MgO	6.22%	4.50%	4.66%	4.62%	3.39%
P_2O_5	4.57%	5.24%	4.89%	5.23%	5.72%
Al_2O_3	4.12%	2.72%	5.52%	3.80%	3.46%
Fe_2O_3	4.02%	2.83%	3.01%	8.86%	3.10%
Others	1.87%	4.19%	1.86%	5.94%	2.93%

PKS ash type

CaO and K_2O are the second major components, but they exhibit greater variation than SiO_2. Adolina II appears to be the best source, as it has the highest SiO_2 content and relatively low impurities. BM I, by contrast, may pose a greater challenge for silica production. It has the highest K_2O content, which could increase acid consumption during metal removal.

The variability in SiO_2 content (46.27-65.18%) implies that for every ton of PKS ash, the theoretical silica yield can vary significantly, i.e., from ~462.7 to ~651.8 kg. It means that, depending on the source, the plant may gain or lose nearly 190 kg of silica per ton of ash. This variation will not only affect production costs and revenue but also equipment utilization and overall process efficiency. With such a wide compositional range, the equipment must be designed to accommodate ash-composition fluctuations while maintaining silica product purity. Given the variations in PKS ash composition, a sensitivity analysis is required to assess their effects on process feasibility and economic robustness.

Fig. 1 presents the base-case batch material and energy flow distribution across the silica production route. In this context, "base case" refers to 1000 kg/batch ash throughput using Adolina II. The diagram shows that the route for producing silica from PKS ash is dominated by treatments with relatively high demand for HCl and NaOH, as well as washing water demand across multiple filtration stages. Beyond material consumption, the gelation, aging, and drying units have the highest thermal energy loads, indicating that these stages are the primary utility bottlenecks. This process-wide propagation pathway provides the mechanistic basis for subsequent economic sensitivity analyses, particularly highlighting the dominance of chemical costs and the strong influence of feedstock variability on MSP and IRR.

To capture the industrial reality of PKS ash silica production, we evaluated economic robustness under a two-dimensional uncertainty framework involving PKS ash compositional variability and fluctuations in ash input capacity. This approach defines a feasible profitability envelope rather than a single deterministic economic outcome.

3.1. Effect of SiO_2 composition on production cost

Figure 2 illustrates the relationship between SiO_2 content in PKS ash and production cost per kg of silica. This diagram was created using Adolina II ash with a production capacity of 1000 kg/batch and an MSF of USD 100,000/ton.

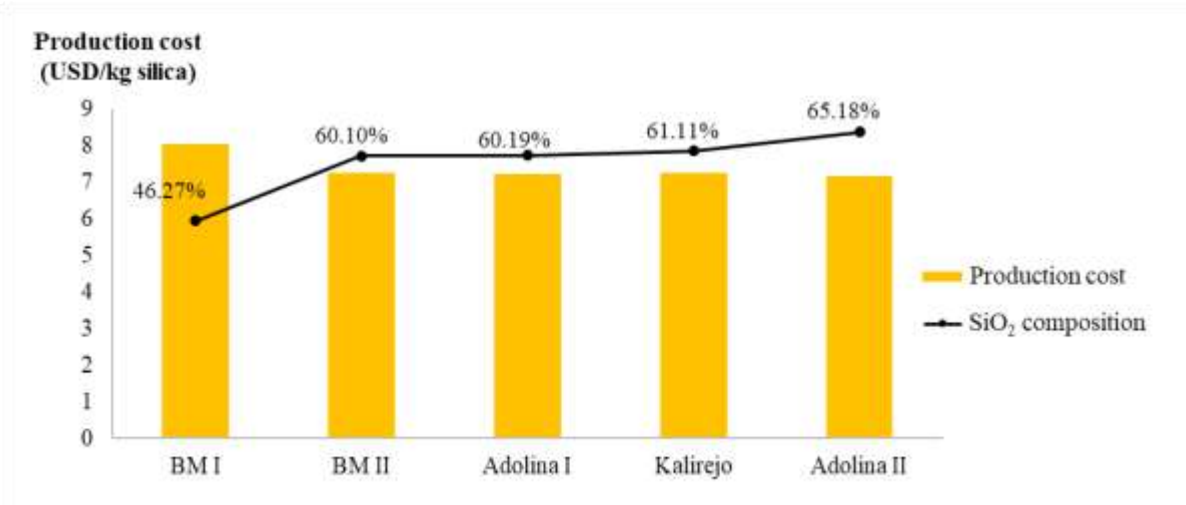

Figure 2. Comparison between the SiO_2 content in PKS ash and the respective production cost per kg of silica.

The diagram was constructed using Adolina II ash at a throughput of 1000 kg/batch and MSP USD 100,000/ton.

It is not surprising that PKS ash with a higher SiO_2 content results in lower production costs per kilogram of silica, since the same amount of raw ash yields more recoverable silica. As shown in Fig. 2, BM I incurs higher production costs, attributable to two factors. First, the lower SiO_2 content reduces the theoretical maximum silica yield, hence directly increasing the cost per kg of product. Second, BM has a more diverse impurity profile, which increases the acid demand for leaching and water usage in purification steps.

However, higher SiO_2 content increases cash outflows. To validate the sensitivity of annual production costs, Fig. 3 depicts the sensitivity analysis for various raw material sources. The figure shows that processing Adolina II, which contains higher recoverable silica, increases total variable expenses due to NaOH consumption for sodium silicate formation, purification, drying, and product handling. This means variability in PKS ash composition will affect daily plant economics. It can create uncertainty in chemical demand, affecting working capital, as well as fluctuations in product output.

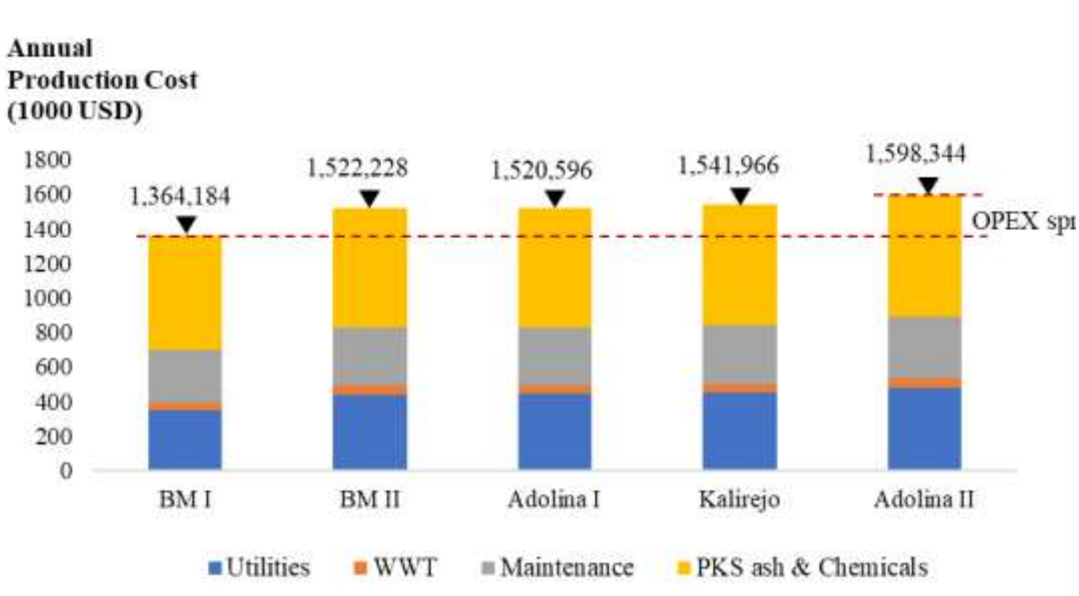

Figure 3. Economic Sensitivity of Silica Production Cost to PKS Ash Composition

The stacked annual production cost in Fig. 3 shows that chemicals are the dominant cost contributor for all ash composition scenarios. This is common in industries that use biomass-based raw materials, where extensive chemical pretreatments are often required to break down the recalcitrant structure of biomass before processing (Bharadwaj et al., 2023; Galbe and Wallberg, 2019). Interestingly, utilities also absorb a significant portion of the cost, suggesting sensitivity to utility tariffs. Nearly all utility expenses are for electricity, with 90% of the demand originating from the 12 h hydrolysis and aging stages. This indicates that this unit operation is the most energy-intensive part of the whole process. The extended aging time significantly increases the energy required for agitation and temperature control, directly amplifying the annual operating expenditure. This finding suggests that optimization of the silica gelation step, such as reducing hydrolysis and aging durations and improving mixing efficiency, should be prioritized to lower total production costs and improve profitability.

The analysis of production cost spread due to raw material compositional variability provides a practical basis for estimating the cash reserve range. It suggests that plant owners should prepare an annual working capital buffer capable of absorbing approximately 17% variation in operating expenditure to ensure stable profitability despite the fluctuating ash quality.

3.2. Effect of PKS ash composition on minimum selling price

The analysis examined how variations in PKS ash composition affect the minimum selling price (MSP) required to maintain the target internal rate of return (IRR) of 22%. The MSP was selected as a key economic response variable because it captures the feedstock variability, chemical demand, and process bottlenecks. Annual net profit provides insight into plant productivity and potential revenue. However, it does not quantify fluctuations in working capital requirements arising from variability in process conditions.

As shown by the black line chart in Fig. 4, there is no linear relationship between SiO_2 content and MSP. The column chart also shows that while NaOH consumption is governed by the SiO_2 fraction, acid requirement does not follow the same trend. In fact, MSP somewhat follows acid usage, with higher acid resulting in higher MSP.

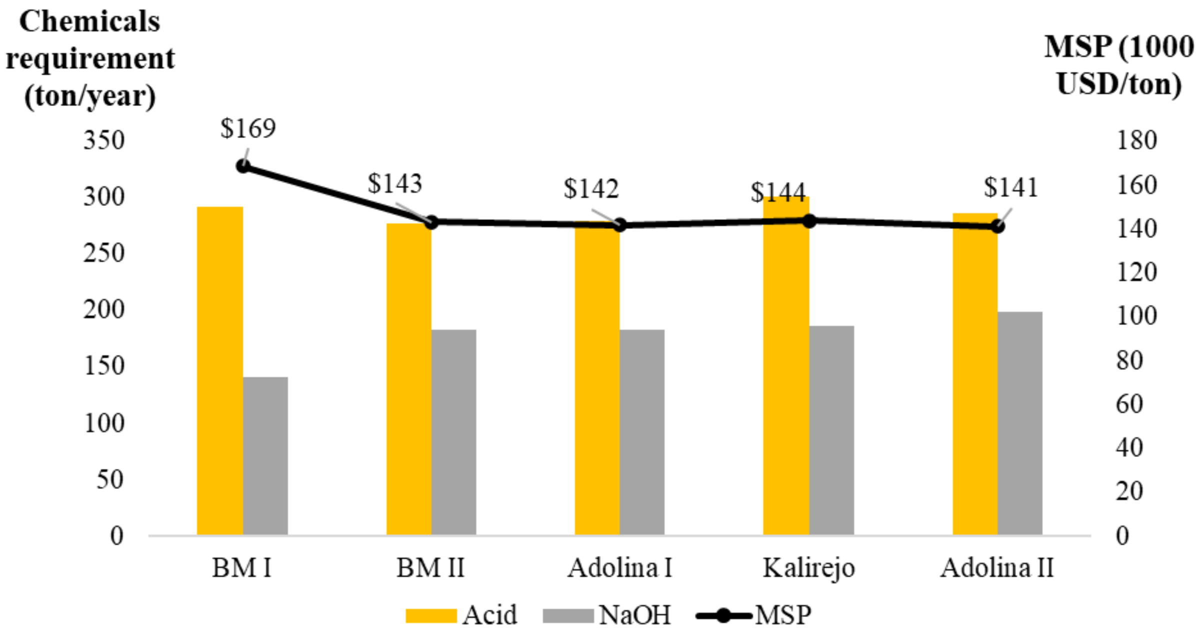

Figure 4. MSP comparison across PKS ash at various compositions

A higher silica fraction generally increases product yield and, thus, revenue potential. However, as SiO_2 content increases, the demand for NaOH in sodium silicate formation rises, thereby increasing MSP. For instance, Adolina II has the highest SiO_2 content, making it the largest consumer of NaOH to convert all silica into sodium silicate. Consequently, the amount of acid required to neutralize the silicate to SiO_2 during the gelation process also increases. Further, in this case, MSP is also determined by the number of acid-soluble oxides that drive hydrochloric acid consumption during leaching. For example, Kalirejo has the second-highest acid-soluble oxides (32.45%) and a considerably high SiO_2 content. Therefore, it consumes more hydrochloric acid for both oxide removal and SiO_2 gelation.

Another important observation is that compositional variation will affect fluctuations in water demand, primarily due to dilution by HCl and NaOH and multiple filtration-washing cycles. Although the cost per unit of water is significantly lower than that of chemicals, the large volume of water used results in a total annual cost contribution that is almost on par with acid consumption. This suggests that, for silica production from PKS ash, water should be treated as a composition-sensitive operating expense with the potential to amplify economic impact (Hoerudin, 2024).

Fig. 4 shows that both Adolina I and Adolina II have similar MSP, despite Adolina II having a higher SiO_2 content. These findings show that the potential economic benefit of higher SiO_2 content can be offset by increased chemical consumption. In this case, the trade-off between impurities that drive acid demand and silica content that determines alkali consumption controls the MSP, not SiO_2 content alone.

Biomass-derived ash composition is inherently difficult to predict. Overall boiler operating conditions, such as combustion temperature, residence time, and excess air, can exacerbate random variation in the resulting PKS ash chemistry. Therefore, because a single optimum PKS ash source may not exist, the focus should be on setting realistic profitability expectations, adjusting operating cost structures, and optimizing process efficiency (Maj et al., 2025). As a result, the plant owner must choose the best pricing strategy to select the MSP that maximizes revenue while keeping IRR within the desired range despite compositional variation.

For instance, Fig. 5 illustrates the profitability uncertainty band at the lowest and highest MSPs for the given PKS ash sources at 1000 kg/batch throughput. In those scenarios, the net profit per unit of silica ranges from 18,000 to 28,000 USD/ton. In this case, rather than identifying a single deterministic return value, this range-based analysis provides a more practical expectation envelope for investment planning, debt servicing, and working capital allocation.

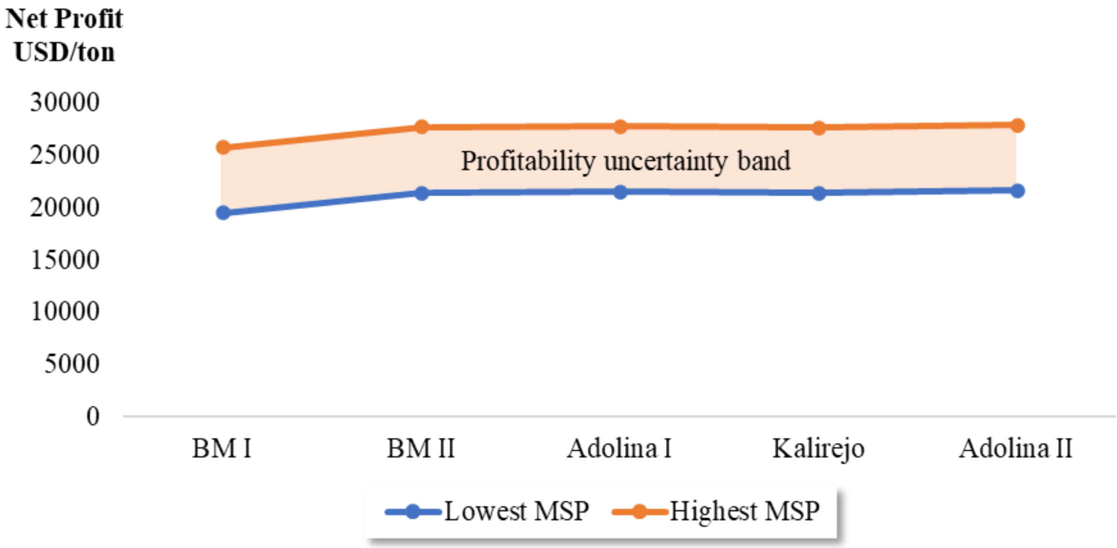

Figure 5. Profitability uncertainty band at the lowest and highest MSP and various ash compositions

3.3. Effect of plant capacity on IRR and MSP

The PKS ash supply from oil palm mills depends largely on boiler load, mill throughput, and combustion efficiency. This variability introduces the second layer of uncertainty beyond ash composition (Ermadani et al., 2024). Therefore, we also analyzed IRR sensitivity to fluctuations in plant load capacity. We evaluated capacity sensitivity using BM I and Adolina II as representatives of ash inputs with the lowest and highest SiO_2 content, respectively. Analyzing the two extremes helps define a profitability operating envelope within which the realized IRR is expected to fluctuate. For this analysis, we used the selected MSP, USD 100,000, at an ash throughput of 1000 kg/batch.

The capacity sensitivity analysis in Fig. 6 shows that throughput's effect on profitability is strongly composition dependent. For both PKS ash scenarios, over the range of 1000-3500 kg/batch, the IRR increases rapidly with ash input capacity but then enters a diminishing-returns region from 4000 kg/batch onward. At the given MSP, Adolina II reaches the targeted 22% IRR at approximately 3500 kg/batch, whereas BM I requires nearly 6500–7000 kg/batch to achieve the same return. This demonstrates that the minimum viable throughput required to achieve the targeted IRR is directly governed by uncertainty in feedstock composition (Wang et al., 2026).

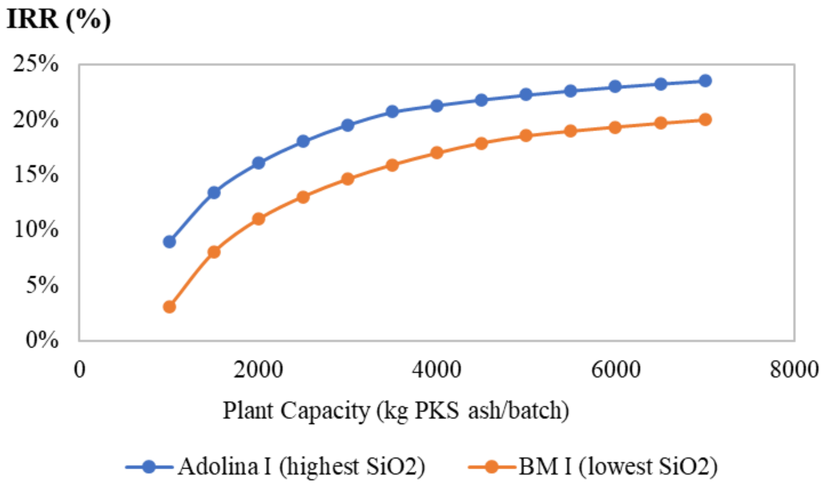

Figure 6. IRR trend on silica production using PKS ash at the highest and lowest SiO_2 content

Furthermore, Figure. 7 shows that the MSP decreases most sharply in the lower-capacity region (1000–2000 kg PKS ash/batch) and gradually approaches a plateau at higher throughput. This trend suggests that some costs do not rise in direct proportion to the batch load, allowing the cost per unit silica to decrease as more ash is processed. For example, increasing plant capacity from 1000 to 2000 kg/batch does not require doubling all equipment, since several process units can still handle the larger load within their design limits. The same applies to labor in batch operation, where the number of operators may remain unchanged because they can prepare for the next step while the current hydrolysis, aging, or filtration process runs (Petrides et al., 2019).
In the lower-capacity region, increasing plant throughput dilutes fixed costs, thereby significantly reducing MSP. At higher capacity, however, fixed costs are already distributed over a sufficiently large production volume, making their contribution relatively small compared with the dominant variable costs, particularly chemicals and utilities (Baral et al., 2026).

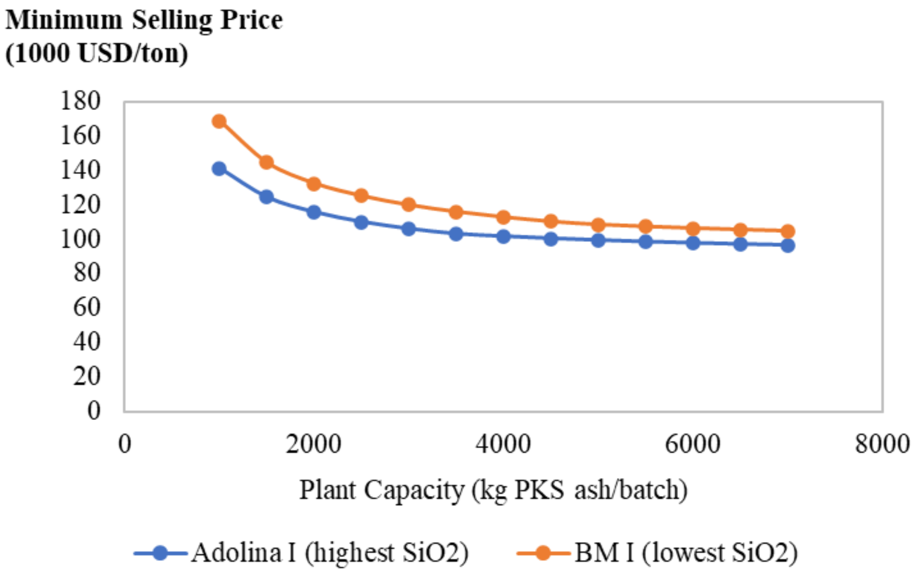

Figure 7. MSP trend on silica production using PKS ash at the highest and lowest SiO_2 content

3.4 Discussion

This study evaluates the techno-economic feasibility of producing high-purity nanosilica from PKS ash under uncertainty in ash compositions and throughput. PKS ashes have a complex and inconsistent chemical composition due to the inherent nature of lignocellulosic biomass and the combustion reaction that thermochemically alters the ash structure. In contrast, semiconductor production demands high-purity silica with a maximum impurity concentration of 1 ppb. Consequently, electronic-grade silica production requires multiple purification cycles, and large acid and alkali consumption is the main source of operational costs.
The material and energy analysis demonstrates that ash composition plays a critical role in determining silica yield, chemical consumption, and utility demand. Variations in SiO_2 content (46–65%) result in substantial differences in theoretical yield and chemical requirements. These variations are a key challenge for plant investors and operators during plant development and operation. As mentioned earlier, PKS ash composition varies because boiler operations in the oil palm mill are not constant. Furthermore, fluctuations in steam requirements for oil palm mill production affect the combustion load, which in turn impacts ash availability for silica production. Consequently, every process variable, such as acid and alkali requirements, is directly affected by compositional variations and, in turn, by operating costs and revenue.
The economic evaluation shows that the economic performance of nanosilica production from PKS ash is governed by dynamics in ash specifications. For instance, Table 1 shows that Adolina II represents the PKS ash type with relatively high SiO_2 content. Fig. 4 shows that when the plant processes such raw material, operators should expect higher NaOH demand for sodium silicate formation, as well as more acid required to neutralize the silicate to SiO_2 during gelation. Consequently, the MSP must also be adjusted, assuming annual profit is held constant. On the other hand, when the plant processes ash with lower SiO_2 (e.g., BM I), NaOH consumption costs are lower, but demand for HCl to remove impurities remains high. For this case, MSP must be elevated even higher to achieve the targeted net profit. Because MSP is limited by the prevailing market

price, annual net profit should not be defined as a single value. In other words, the plant's economic feasibility should be analyzed through a profitability window, allowing plant operating conditions to be adjusted accordingly.

The 17% OPEX spread implies that the plant will also experience variability in working capital. The spread percentage is an approximation based on the ash specifications used in this study; however, it provides valuable insights, especially for the plant owners. The OPEX spread analysis shows that having a savings strategy is crucial to keep the plant running. Even in the worst-case ash-input scenario, the plant would still have a cash buffer to absorb the additional working capital required by increased chemical demand.

Beyond throughput variability, plant capacity significantly affected economic performance. To some extent, increasing throughput improves capital utilization and reduces unit production cost. However, beyond a certain scale, operating costs become the dominant factor; hence, further increases in production capacity have no significant effect on economic performance. The combined effect of compositional variability and fluctuations in PKS ash input highlights the importance of making economic decisions based on evaluation under dual uncertainty.

Repeated washing after each acid and alkali treatment also highlights the silica production from PKS ash. The results show that the total annual cost contribution from water usage is similar to that of acid consumption. This must be considered when improving process efficiency. One goal of recycling PKS ash is to achieve economic circularity by converting it into a higher-value product. However, such an endeavor should be carefully designed to avoid overlooking sustainability.

4. CONCLUSION

Overall, this study provides practical insights for PKS ash-derived nanosilica plant developers and operators on interactions among compositional and throughput variability, process performance, and economic outcomes. The uncertainty-based framework offers a useful approach for assessing emerging biomass-to-material processes. It provides foundational support for developing alternative, non-mined silica sources to complement conventional quartz-based ones. Future work should incorporate additional uncertainties relevant to the palm oil mill industry, improve process efficiency, and validate the model at pilot scale to provide a solid foundation for scale-up and commercialization.

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AUTHOR CONTRIBUTIONS

Aniek Sri Handayani: Conceptualization, Investigation, Funding Acquisition.

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Yuli Amalia Husnil: Data curation, writing review & editing

Satrio Kunto Laksono: Data Curation, Formal Analysis.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ETHICS STATEMENT

This study did not require ethical approval.

DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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