Silica Recovery from Oil-Palm Combustion Ash: A Critical Review of Recovery Processes, Product Quality and Barriers to Scale-Up

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ABSTRACT

Oil-palm combustion ash can be used to produce silica and silicate products, but the evidence supporting commercial production remains unclear. This review examines recovery methods, product quality and barriers to scale-up across 48 retrieved reports published between 2013 and 2026. Reports were identified through database searches and eligibility screening, then assessed through a critical narrative synthesis. Five route groups were identified: acid leaching, alkaline extraction and precipitation, templated mesoporous silica synthesis, silicate solution production, and other recovery methods. Selected studies reported approximately 95–97% SiO_2 by X-ray fluorescence after alkaline extraction and precipitation. Some recovered silicate activators also produced mortar strengths close to those of commercial controls. However, differences in analytical methods, sample types and reporting bases prevented direct comparison of product purity. Only 15 reports provided numerical yield-related values, and inconsistent definitions limited comparison of overall silica recovery. Information needed to assess scale-up was also scarce. Fourteen reports stated some water-use quantities, seven discussed effluent or by-product handling, and one provided an energy/cost estimate with an unclear process boundary. No included report demonstrated extraction-reagent recycling, recovery beyond laboratory scale, or a quantitative process life-cycle assessment. Unresolved screening decisions, unavailable reports and overlapping datasets limit the review's coverage and interpretation. The findings support laboratory feasibility under specific conditions, but do not establish commercial readiness or economic and environmental advantages. A minimum reporting checklist is proposed to improve analytical consistency, mass balances, feedstock assessment, commercial benchmarking and the data needed for techno-economic and life-cycle assessment.

Keywords: Palm oil fuel ash, Boiler ash, Silica, Waste valorisation

Statement Of Novelty

This review assesses what the available evidence establishes about the quality and commercial potential of silica-containing solids and silicate solutions recovered from oil-palm combustion ash. It examines how analytical methods and reporting bases affect composition comparisons, and distinguishes silica extracted into solution from silica recovered in the final product. It also evaluates whether reported process inputs, outputs and application tests support claims of commercial readiness. A product-specific minimum reporting checklist is proposed to improve comparisons between studies and guide future scale-up assessment.

INTRODUCTION

Indonesia and Malaysia together supply most of the world's palm oil. For the 2025/26 marketing year, the United States Department of Agriculture estimated 46.7 Mt (57.3% of world production) for Indonesia and 20.2 Mt (24.8%) for Malaysia (United States Department of Agriculture, Foreign Agricultural Service, 2026).

Malaysian crude palm oil production in 2025 was 20.28 Mt (Malaysian Palm Oil Board, 2026). Palm oil mills burn mesocarp fibre and kernel shell in their boilers to raise steam (Awalludin et al., 2015; Thomas et al., 2017). The resulting ash, called palm oil fuel ash (POFA), palm oil mill fly ash (POMFA) or palm oil boiler ash (POBA), has mostly been studied as a supplementary cementitious material, and construction reviews describe it as a waste largely disposed of in landfill (Hamada et al., 2018, 2021; Thomas et al., 2017).

Biomass ash composition depends on the fuel, combustion technology and collection point, and can vary substantially within a fuel type (Lehmusto et al., 2024; Vassilev et al., 2013; Voshell et al., 2018). Among the included reports, measured SiO_2 contents of industrially generated ash and clinker ranged from 27.3 wt% (Bukit et al., 2022) to 61.6 wt% (Ghanim et al., 2025). Potassium, calcium, iron and unburnt carbon were other important constituents. This variability makes feedstock characterisation and process control essential for producing materials of consistent quality.

Alkaline dissolution followed by acid precipitation has been used to recover amorphous silica from rice husk ash for more than two decades (Kalapathy et al., 2000), and several reviews cover silica from agricultural residues (Abdul Razak et al., 2022; Rohimah et al., 2026; Saha et al., 2024; Yadav et al., 2022). Reviews focused on palm ash are fewer. Wardanu et al. (2024) reviewed POFA-derived silica nanoparticles for water purification without reporting a search method. Rohimah et al. (2026) reviewed biogenic silica from several agro-industrial wastes, including palm oil boiler ash. Costa and Paranhos (2020) and Oyehan et al. (2022) discussed palm ash in relation to mesoporous materials and POFA modification, respectively. Construction reviews mainly assess POFA as a pozzolan (Hamada et al., 2019, 2021; Liew et al., 2024; Santhosh et al., 2022). The reviews discussed above do not provide a consistent process-level comparison that distinguishes analytical bases, yield definitions and the evidence needed for scale-up.

This review examines that gap for silica-containing products recovered from oil-palm combustion ash, with particular attention to their relevance to Southeast Asian palm oil production. The objectives were to (i) map the recovery routes and products reported in peer-reviewed studies; (ii) assess the comparability of reported composition, yield and performance; (iii) describe the availability of process, safety, cost and scale information; and (iv) propose a minimum reporting checklist for future work.

METHODS

Review design

This review used database searches and eligibility screening to identify relevant reports, followed by a critical narrative synthesis of their methods and findings. The reporting structure followed relevant elements of the PRISMA 2020 statement, adapted where appropriate for laboratory process studies (Page et al., 2021). Meta-analysis was not performed because the reports used different analytical bases, yield definitions, product types and performance tests. These differences prevented meaningful statistical pooling of the results.

Eligibility criteria

Primary research reports were eligible if they described the production and characterisation of a silica-containing material or silicate solution from oil-palm combustion ash. Product classes included silica gel, precipitated silica, nanosilica, mesoporous silica, chemically enriched ash, and sodium or potassium silicate solutions. Industrially generated feedstocks comprised mill boiler, fuel or fly ash and palm oil clinker. Laboratory-produced feedstocks comprised ash prepared by burning empty fruit bunches, kernel shells or kernels and these were identified separately. Records were excluded when ash was used only as an unextracted construction or geopolymer ingredient (E1), the recovered product was a zeolite (E2), the feedstock was not oil palm (E3), the publication was a review (E4, retained for citation searching), ash was used directly without producing a target material (E5), or the record was off-topic, front matter or an erratum (E6). Commercial sodium silicate used merely to activate POFA fell under E1.

Information sources and searches

Scopus and Web of Science Core Collection were searched using three concept blocks combined with AND: (A) feedstock terms, including palm oil fuel ash, boiler ash, fly ash, clinker and their abbreviations; (B) product terms, including silica, silica gel, precipitated silica, nanosilica, mesoporous silica and sodium silicate; and (C) process terms, including extraction, leaching, precipitation, synthesis and sol–gel. The main searches returned 144 Scopus and 107 Web of Science records. Broader searches without block C identified an additional 287 Scopus and 224 Web of Science records absent from the main search sets. These additional records were screened separately. No publication-year restriction was applied. The 762 records were deduplicated by DOI and then by normalised title, removing 269 duplicates and leaving 493 unique records. Titles and abstracts were screened against the eligibility criteria. Full texts were sought for all included records.

Data extraction and verification

A structured form was used to record information from each report. This included publication details, feedstock origin and composition, analytical methods, and product type. Process information covered pretreatment, extraction and precipitation conditions, together with any templates or modifiers used. For each product, the form recorded the reported SiO_2 or elemental silicon (Si) content, the basis on which the composition was expressed, impurities, specific surface area, identified phases and particle characteristics. Yield-related values were recorded together with the process stage they described and the quantity used as the denominator. Where the denominator was not explicitly stated but could be inferred, this interpretation was noted. Additional information included silicate modulus, reported dissolution efficiency, application tests, comparisons with commercial materials, and energy and cost estimates. Claims that required qualification were also recorded, particularly where the reported measurements did not fully support the interpretation presented..

Reporting indicators and author-group mapping

Reporting completeness was assessed using 22 indicators covering feedstock, product, process and scale-up information. For each indicator, the number of reports providing the relevant information was counted across the 48 included reports. These counts describe what was reported and they are not a validated measure of study quality. Each indicator must also be interpreted according to the product studied. For example, powder surface area and phase analysis are not relevant to every liquid silicate activator.

Analytical information was classified according to the material examined and the method used. Material categories comprised solid materials, intermediate solutions, and products from silicate or silica solution routes. Analytical methods included X-ray fluorescence (XRF), energy-dispersive X-ray spectroscopy (EDX/EDS), inductively coupled plasma analysis (ICP), atomic absorption spectroscopy (AAS), qualitative X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR). Cases where the analytical basis was not reported were recorded separately. Analyses of dried residues from solution routes were clearly identified. For yield-related values, the reported calculation basis was recorded separately from whether the available data supported a valid mass balance.

Reports were grouped when they shared a first or senior author, or several co-authors. This approach identified 22 author groups. A broader grouping rule, which also merged groups linked by a shared co-author, reduced the number to 20. Reuse of identical data within groups was recorded separately. Elemental silicon (Si) values were also distinguished from silicon dioxide (SiO_2) values. Pure SiO_2 contains approximately 46.74 wt% Si, calculated as $28.086/60.084 \times 100$.

OVERVIEW OF THE EVIDENCE BASE

Study selection and characteristics

Of the 493 unique records, 420 were excluded at title and abstract screening, most commonly because the ash was used only in construction or geopolymer materials (249 records). 49 records were sought in full text. One

of the 49 assessed reports was excluded because it described thermal calcination only, with no silica product, leaving 48 included reports. The 48 included reports were published between 2013 and 2026 with 42 appeared in 2018 or later. Thirty were classified as journal articles, 15 as conference papers, and three as journal publications labelled as a conference volume, conference special issue or case report. By stated ash origin, 18 used Malaysian material, 13 Indonesian, five Thai, two Nigerian and one Indian. Nine did not specify the origin. Author affiliation was not substituted for feedstock origin.

Forty-three reports used industrially generated feedstock. Forty used mill boiler, fuel or fly ash, variously labelled POFA, POMFA, POBA or OPBA, and three used clinker. Five used laboratory-produced ash from empty fruit bunches (Agi et al., 2022; Rahmat et al., 2021), kernel shells (Imoisili et al., 2020a, 2020b) or kernels (Saharudin et al., 2018). Seventeen reports did not test an end-use application of the silica product. The proposed uses were kept separate from demonstrated applications. The most common tested applications included catalyst supports (10 reports), geopolymer activators (six) and cement/concrete additives (five). Figure 1 presents publication years and route groups.

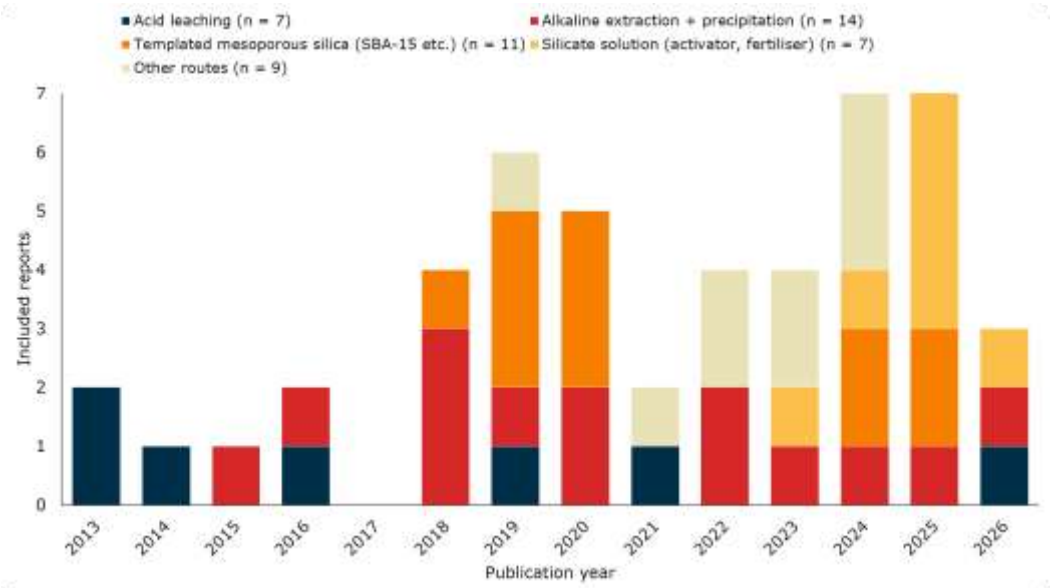

Figure 1 Included reports by year of publication and recovery route (n = 48)

Author groups and overlap in reported datasets

The 48 reports originated from 22 author groups, or 20 under the broader grouping rule. Several reports contain overlapping numerical datasets. Four papers by Faizul and co-workers report the same citric-acid leaching dataset and the same product purity 92.00% SiO_2 (Faizul et al., 2013a, 2013b, 2014; Pa et al., 2016). Several Universiti Malaysia Pahang papers repeat raw and leached SiO_2 values of 47.71% and 85.46%, although some other composition entries differ slightly (Abdullah et al., 2018, 2020a; Razak et al., 2019, 2019a, 2019b). Two papers report matching SBA-15 textural characteristics (Abdullah et al., 2020, 2020b), and another pair share support textural values (Razak et al., 2019a, 2019b). The Universitas Gadjah Mada papers repeat surface-area, pore-diameter and pore-volume values (Kusumaningtyas et al., 2024; Sitohang et al., 2024). Two Prince of Songkla University papers report identical response-surface summary statistics for different response descriptions (Utama et al., 2018a, 2019). Related Universiti Malaya reports repeat a treated-POFA SiO_2 value of 60.3% (Alengaram et al., 2024; Alnahhal et al., 2023; Hui et al., 2025), and the two kernel-shell papers report 54.35% yield (Imoisili et al., 2020a, 2020b).

These overlaps can reflect shared materials, characterisation or reporting errors, but matching values alone do not determine which explanation applies. Differences in mill naming also do not establish distinct physical sources without further documentation. Related prior work is acknowledged in some papers (Abdullah et al., 2020). Disclosure must therefore be assessed at the specific dataset level. The 48-report count should not be equated with 48 independent feedstock datasets, but neither can author-group counts establish the number of independent experiments.

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RECOVERY ROUTES AND PRODUCTS

The eight coded route categories were grouped into five for presentation: acid leaching, alkaline extraction and precipitation, templated mesoporous silica, alkali silicate solutions, and other routes. The last group includes KOH fusion, milling with chemical treatment, water extraction, glycol dissolution, calcium silicate production, and thermal treatment followed by milling. Table 1 identifies the reported material and analytical basis. Values may refer to different process stages or selected experimental conditions and are labelled accordingly.

Table 1 Characteristics of the 48 included reports, ordered by recovery route and year

Report	Feedstock	Route	Product	SiO_2 (wt%)*	Basis	Yield (%) (definition)	BET (m^2/g)	Applica-tion tested
Faizul et al. (2013b)	Mill ash	Acid leaching	silica-enriched ash	92.00	XRF oxide	NR	NR	none
Faizul et al. (2014)	Mill ash	Acid leaching	silica-enriched ash	92.00	XRF oxide	NR	NR	none
Pa et al. (2016)	Mill ash	Acid leaching	silica-enriched ash	92.00	qual./NR	NR	NR	none
Razak et al. (2019)	Mill ash	Acid leaching	silica-enriched ash	85.46	XRF oxide	NR	6.95	catalyst support
Rahmat et al. (2021)	EFB ash (lab)†	Acid leaching	silica-enriched ash	45.6	XRF oxide	NR	NR	optical ceramic
Manurung et al. (2026)	Mill ash	Acid leaching	silica-enriched ash	95.6 (EDX norm.)	EDX	NR	0.24	CO_2 adsorbent
Irfan Khan et al. (2015)	Mill ash	Alkaline extract-ion + precipitation	Nano-silica	NR	qual./ NR	NR	326	none
Utama et al. (2016)	Mill ash	Alkaline extraction + precipitation	precipitated silica	94.92	XRF oxide	NR	NR	none (filler proposed)
Saharudin et al. (2018)	Kernel ash (lab)†	Alkaline extraction + precipitation	acidified silica sol	NR	Solu-tion	NR	NR	coating
Utama et al. (2018)	Mill ash	Alkaline extraction + precipitation	precipitated silica	NR	EDX	60.11 (SiO_2 recovery, calc.)	53.59	none (filler proposed)
Utama et al. (2018a)	Mill ash	Alkaline extraction + precipitation	silica gel	95.33	XRF oxide	60.42 (SiO_2 conversion)	NR	none
Utama et al. (2019)	Mill ash	Alkaline extraction + precipitation	precipitated silica	96.9	XRF oxide	~200 g/kg (estimate)	138	none
Imoisili et al. (2020a)	PKS ash (lab)†	Alkaline extraction +	nanosilica	96.59 (EDX	EDX	54.35 (undefined)	438	none

		precipitation		Si+O)				
Imoisili et al. (2020b)	PKS ash (lab)†	Alkaline extraction + precipitation	silica gel	96.83	XRF oxide	54.35/56.65 (undefined)	NR	none
Utama et al. (2022)	Mill ash	Alkaline extraction + precipitation	precipitated silica	Si 39.3	EDX	80.01/81.01 (undefined)	198.55	none
Novita and Idris (2022)	PKS ash (plant, re-ashed)	Alkaline extraction + precipitation	silica gel	45.13	XRF oxide	34 (undefined)	NR	desiccant
Kunchari-yakun et al. (2023)	Mill ash	Alkaline extraction + precipitation	nanosilica	89.44	XRF oxide	NR	323	cement/ concrete
Hoerudin et al. (2024)	Mill ash	Alkaline extraction + precipitation	amorphous silica powder	94.68	XRF oxide	17.25 (product/ re-ashed ash)	390.80	none
Fynnisa et al. (2025)	Mill ash	Alkaline extraction + precipitation	silica gel	Si ~31.5	EDX	NR	NR	none
Mohd Sufian et al. (2026)	Mill ash	Alkaline extraction + precipitation	amorphous silica powder	Si 35.91	EDX	17 (product/ ash)	NR	adsorbent/p hotocata-lyst
Abdullah et al. (2018)	Mill ash	Templated mesoporous	Ni/SBA-15 (via Na silicate)	40,570 ppm (soln)	ICP (inter-media-te soln)	NR	515 (Ni)	catalyst support
Chong et al. (2019)	Mill ash	Templated mesoporous	Ni/SBA-15 (via Na silicate)	20.16 (soln)	ICP (inter-media-te soln)	NR	179 (Ni)	catalyst support
Razak et al. (2019b)	Mill ash	Templated mesoporous	SBA-15 (via Na silicate)	~61,000 ppm (soln)	ICP (inter-media-te soln)	NR	524.74	catalyst support
Razak et al. (2019a)	Mill ash	Templated mesoporous	SBA-15 (via Na silicate)	61,021 ppm (soln)	ICP (inter-media-te soln)	NR	524.74	catalyst support
Abdullah et al. (2020a)	Mill ash	Templated mesoporous	SBA-15 (via Na silicate)	40,570 ppm (soln)	ICP (inter-mediat e-soln)	NR	330	catalyst support
Abdullah et	Mill ash	Templated	SBA-15 (via	40,570 ppm	ICP (inter-	NR	330	catalyst

al. (2020b)		mesoporous	Na silicate)	(soln)	media-te soln)			support
Cheng et al. (2020)	Clinker	Templated mesoporous	SBA-15	NR	qual./NR	NR	508	catalyst support
Sitohang et al. (2024)	Mill ash	Templated mesoporous	MES-templated silica	Si 39.90	EDX	44.6 (product/ash)	71.0	adsorbent/photocata-lyst
Kusumaningtyas et al. (2024)	Mill ash	Templated mesoporous	MES-templated silica	Si 39.00	EDX	NR	71.0	adsorbent/photocata-lyst
Hasnain et al. (2025a)	Mill ash	Templated mesoporous	SBA-15	NR	qual./NR	NR	487.2	catalyst support
Hasnain et al. (2025b)	Mill ash	Templated mesoporous	SBA-15	NR	qual./NR	NR	238 (Ni)	catalyst support
Alnahhal et al. (2023)	Mill ash	Alkali silicate solution	sodium silicate solution	11–16.8 (soln)	Solu-tion	54–82 (dissolu-tion)	NR	Geopoly-mer activator
Alengaram et al. (2024)	Mill ash	Alkali silicate solution	sodium silicate solution	NR	Solu-tion	NR	NR	Geopoly-mer activator
Ghanim et al. (2025)	Clinker	Alkali silicate solution	sodium silicate solution	40.30 (soln)	Solu-tion	44.5–65.4 (dissolu-tion)	NR	Geopoly-mer activator
Hoerudin et al. (2025)	Mill ash	Alkali silicate solution	K silicate solution	18.50 avail. (soln)	AAS (solu-tion)	12.98 (vol/vol)	NR	fertiliser
Hui et al. (2025)	Mill ash	Alkali silicate solution	sodium silicate solution	32 (one HBSS)	Solu-tion	NR	NR	Geopoly-mer activator
Lazarus et al. (2025)	Mill ash	Alkali silicate solution	sodium silicate solution	51.75 (dried IHS)	Solu-tion	13.46 (dissolu-tion)	NR	Geopoly-mer activator
Sekar and Arunasankar (2026)	Mill ash	Alkali silicate solution	sodium silicate solution	NR	Solu-tion	NR	NR	Geopoly-mer activator
Ayub et al. (2023)	Mill ash	KOH fusion	amorphous silica powder	98 (EDS)	EDX	~80 (SiO_2 recovery)	NR	none
N. Bukit et al. (2019)	Mill ash	Milling + acid/base	milled, treated ash	Si 56.8–65.3 (elem. XRF)	XRF elem-ental	NR	NR	none (filler proposed)
Bukit et al. (2022)	Mill ash	Milling + acid/base	milled, treated ash	48.5	XRF oxide	NR	NR	none (coating

								proposed)
Frida et al. (2024)	Mill ash	Milling + acid/base	SiO_2-ash/TiO2 coating	NR	qual./NR	NR	NR	coating
Satriawan et al. (2021)	Mill ash	Other	$CaSiO_3$ filler	Si 15.65 ($CaSiO_3$)	EDX	0.877 M (concen-tration)	NR	paper filler
Olivia et al. (2023)	Mill ash	Other	precipitated silica	NR	qual./NR	NR	NR	cement/ concrete
Olivia et al. (2024)	Mill ash	Other	precipitated silica	53.02	XRF oxide	NR	NR	cement/ concrete
Ismail et al. (2024)	Clinker	Other	soluble silica (glycol)	53.50 (oxide share)	solutio n	NR	NR	cement/ concrete
Agi et al. (2022)	EFB ash (lab)†	Thermal + milling	crystalline nanosilica	94.46	XRF oxide	NR	NR	oil recovery

* SiO_2 content as reported, on the basis shown. "Si" denotes elemental silicon (pure SiO_2 contains 46.74 wt% Si). soln, value for a silicate solution; norm., normalised; EDX includes EDS; qual., qualitative. Mill ash includes ash labelled POFA, POMFA, POBA or OPBA by the authors. †Secondary feedstock (laboratory-made ash). Ni, value for the nickel-loaded catalyst. NR, not reported.

Acid leaching to silica-enriched ash

Acid leaching removes acid-soluble constituents and can leave a silica-enriched solid rather than newly synthesised silica (Rahmat et al., 2021; Razak et al., 2019). Citric-acid leaching followed by re-combustion produced material reported as 92.00% SiO_2 by XRF (Faizul et al., 2013a). Loss on ignition (LOI) was not reported, and a related paper identified residual carbon and quartz by XRD (Pa et al., 2016). A later study reported 95.6% elemental Si in an EDX table that omitted oxygen and totalled 100% across the listed components (Manurung et al., 2026). This apparent selected-element basis does not establish whole-sample SiO_2 purity.

Hydrochloric-acid treatment increased reported SiO_2 from 47.71% to 85.46%. The leached ash assigned crystalline phases to cristobalite and reported 6.95 m^2/g (Razak et al., 2019). Sulphuric-acid leaching of laboratory EFB ash left 45.6% SiO_2, 17.8% CaO and 16.4% K_2O (Rahmat et al., 2021). Where reported, diffraction indicated retained crystalline phases (Manurung et al., 2026; Pa et al., 2016; Rahmat et al., 2021; Razak et al., 2019) and three related leaching studies did not report XRD (Faizul et al., 2013a, 2013b, 2014). Acid leaching is therefore appropriately treated as beneficiation, and the products should not automatically be described as synthetic amorphous silica.

Alkaline extraction and precipitation

The most common recovery route dissolves silica in heated NaOH and precipitates it from the filtrate using acid or CO_2. Reported conditions vary substantially, including NaOH concentrations of approximately 1–3 M or 6–10 wt%, temperatures of 80–120 °C and extraction times commonly within 1–4 h (Hoerudin et al., 2024; Imoisili et al., 2020a, 2020b; Kunchariyakun et al., 2023; Utama et al., 2016, 2019).

A Thai POMFA study reported 60.42 ± 0.83% extraction of feedstock silica into the filtrate by ICP-OES. The subsequently isolated gel contained 95.33% SiO_2 by semi-quantitative XRF (Utama et al., 2018a). The extraction percentage does not establish final recovery after gel formation and washing. The reported Na_2O

content of 2.50% exceeded the cited 0.2–2.4% specification range. Another product contained 94.92 ± 0.12% SiO_2 against a cited ≥95% criterion, and 0.07 ± 0.06% Fe_2O_3 against a 0.05% limit (Utama et al., 2016). These point estimates and their uncertainty do not demonstrate full specification compliance.

CO_2 precipitation produced material reported as 96.90 ± 0.21% SiO_2 and 138 m²/g (Utama et al., 2019). A related 60.11% extraction value was calculated indirectly assuming fixed carbon in the residue (Utama et al., 2018). For Indonesian POMFA, the reported yield was 80.01% (Utama et al., 2022).

Hoerudin et al. (2024) reported a product-mass yield of 17.25 ± 1.30%, 94.68% SiO_2 and 390.80 m²/g for re-ashed POFA extracted with 10% NaOH after citric-acid leaching. These values identify the highest-yield condition, not the maximum composition or surface area across all treatments. The study reported up to 95.44% SiO_2 and 447.51 m²/g. They also analysed a commercial precipitated silica that contained 94.00% SiO_2 and had an area of 137.59 m²/g.

The same study tabulated crystallinity indices of approximately 46–51% for products and 53.90% for the commercial amorphous comparator, while displaying broad diffraction humps for these materials (Hoerudin et al., 2024). This inconsistency questions the interpretation of the index, not proof that the products contain approximately 50% crystalline silica. Synthetic amorphous silica is conventionally characterised as X-ray amorphous (Fruijtier-Pölloth, 2012). Therefore, quantitative crystalline-phase fractions cannot be inferred from the reported index without a validated phase-analysis method.

Other alkaline-extraction studies provide less complete or less readily comparable characterisation. Laboratory kernel-shell silica contained 96.83% SiO_2 by XRF, but the same report used 54.35% and 56.65% in content/yield descriptions and also called the composition value a yield (Imoisili et al., 2020b). A companion paper described 96.59% as the EDX sum of Si and O and reported 438 m²/g (Imoisili et al., 2020a). That elemental sum is not an oxide-purity determination. Thai POFA nanosilica contained 89.44% SiO_2 with 2.24% Na_2O, 4.21% K_2O and 3.86% Al_2O_3 (Kunchariyakun et al., 2023). These constituents were considered in relation to belite cement formation, illustrating that acceptable composition depends on the application.

Polyethylene-glycol-assisted precipitation produced 326 m²/g without a quantitative silica-product composition (Irfan Khan et al., 2015). A kernel-shell product tested as a medicine-packaging desiccant contained reported values of 45.13% SiO_2 and 45.55% NaCl and showed crystalline phases (Novita & Idris, 2022). In Fynnisa et al. (2025), 92.18% SiO_2 and approximately 189.20 m²/g concerned the zeolite-derived comparator, whereas the POBA product had approximately 31.5% elemental Si by EDX. Other application tests included methylene-blue adsorption, with a fitted Langmuir capacity of approximately 198 mg/g and composition by EDX (Mohd Sufian et al., 2026), and a coating made using an acidified silicate sol, achieving a water contact angle of 156 ± 1° (Saharudin et al., 2018). Overall, alkaline recovery is demonstrated at laboratory scale, but final recovery and product-grade claims remain dependent on the measurement basis.

Templated mesoporous silica

Eleven reports used ash-derived silicate to prepare mesoporous materials. Nine concerned SBA-15, commonly templated with Pluronic P123 and investigated as catalyst supports while two used a methyl ester sulfonate template (Abdullah et al., 2018, 2020a, 2020b; Cheng et al., 2020; Chong et al., 2019; Hasnain et al., 2025a, 2025b; Kusumaningtyas et al., 2024; Razak et al., 2019a, 2019b; Sitohang et al., 2024). Silicate preparation included NaOH fusion of acid-leached ash at an ash:NaOH mass ratio of 1:2 and 550 °C for 1 h, or alkaline reflux (Abdullah et al., 2018, 2020a, 2020b; Chong et al., 2019; Hasnain et al., 2025a, 2025b).

BET surface areas of POFA-derived SBA-15 were 330–525 m^2/g (Abdullah et al., 2020b; Razak et al., 2019b), against 598.67 m^2/g for SBA-15 made from commercial sodium silicate in the same study (Razak et al., 2019b). The nickel-loaded POFA catalyst, however, had a higher surface area than its TEOS-derived counterpart (515 versus 473 m^2/g) (Abdullah et al., 2018). For clinker, SBA-15 reached 508 m^2/g against 642 m^2/g for the commercial-precursor material (Cheng et al., 2020).

Catalytic comparisons were mixed. One report described CH_4 conversion as 31.5% higher for a TEOS-derived catalyst than for its POFA counterpart (Abdullah et al., 2018). Another reported numerically close conversions of 91.4% and 92.1% for ash-derived and commercial-silicate catalysts (Chong et al., 2019). Cheng et al. (2020) reported favourable clinker-catalyst performance, but the often-quoted 73.33% and 28.96% ethanol conversions arise from different operating regimes. The former was obtained during an optimised 400 °C, 50 wt% ethanol, 16 mL/g·h run while the latter was the commercial catalyst maximum at 350 °C, 99.5 wt% ethanol and 12 mL/g·h. They are not a matched-condition effect estimate.

The nine SBA-15 reports did not establish bulk oxide purity of the final silica support. Intermediate-silicate ICP values, including 40,570 and 61,021 ppm, were variously described as silicon or silica content and require an explicit analyte and concentration basis (Abdullah et al., 2018; Razak et al., 2019a). The purity of the support, and the effect of residual alkali and iron from the ash on catalyst performance, therefore remain unknown.

The two methyl-ester-sulfonate studies reported areas of 71.014 m^2/g and pore diameters of 7.923 nm for templated products, compared with 41.033 m^2/g and 4.180 nm without the template (Kusumaningtyas et al., 2024; Sitohang et al., 2024). These reported diameters lie within the conventional mesopore range of 2–50 nm. Low surface area alone does not invalidate the mesoporous designation. Ordered pore structure is a separate characterisation question. Composition was reported as elemental Si by EDX (39.90 and 39.00 wt%), and the sources assigned crystalline silica phases after calcination at 750 °C or above. Sitohang et al. (2024) explicitly reported 4.46 g product from 10 g ash, a product-mass yield of 44.6%, and tested fatty-acid removal from crude palm oil while the companion study tested methylene-blue removal (Kusumaningtyas et al., 2024).

Alkali silicate solutions

Seven reports investigated liquid silicate products, six as geopolymer activators and one as a liquid fertiliser. Alnahhal et al. (2023) reported solution SiO_2 contents of 11–16.8% and dissolution values of 54–82%. Mortar made using the resulting activator reached 51 MPa at 28 days, compared with 52 MPa for the commercial-silicate control. A clinker-derived activator produced mortar with 58.9 MPa at 56 days against 62.9 MPa for the commercial control (Ghanim et al., 2025). Its reported 44.48–65.42% yield values equal ratios of post-extraction and raw-material composition percentages. Without an explicit compatible mass balance, these ratios do not independently validate silica mass recovery.

Related work reported silicate moduli (SiO_2:Na_2O ratios, with the mass or molar basis to be specified) of 0.96–1.5 (Hui et al., 2025). Lazarus et al. (2025) reported 51.75% SiO_2 by XRF of dried silicate residue and described 13.46% dissolution, but did not provide a transparent complete recovery balance. The material was used as a 50:50 blend with commercial silicate, supporting partial rather than complete substitution. A conference report made a superiority claim for rice-husk-derived silicate but this should not be attributed to palm-ash silicate (Alengaram et al., 2024). Sekar and Arunasankar (2026) described commercial-control strength as 39.5 MPa in the text but 45.8 MPa in the table, preventing a secure performance ranking.

The fertiliser study was the only report to test application-specific contaminants against a named national requirement (Hoerudin et al., 2025). Its product contained 18.50 ± 1.50% available SiO_2 and 19.22% K_2O, with Pb at 0.64 ppm and As at 0.17 ppm. The commercial comparator had 20.71% available SiO_2. No plant trial was reported. Its 12.98% yield was concentrate volume divided by solvent volume, not silica recovery. Liquid-product performance is promising under some laboratory conditions, but concentrations, dried-residue compositions and dissolution proxies must remain distinct.

Other routes

KOH fusion of POFA at an ash:KOH ratio of 1:3.5 and 850 °C was reported to yield approximately 80% silica relative to the feedstock silicon oxide and a porous graphene coproduct with 1506.6 m^2/g (Ayub et al., 2023). The paper also made an approximately 98% purity claim, but its reported silica EDS proportions (Si 81.7%, O 18.3%) do not establish stoichiometric SiO_2 purity on an oxygen-inclusive mass basis. The claim therefore remains analytically unresolved.

Three Indonesian studies combined milling with acid/base treatment (Bukit et al., 2019, 2022; Frida et al., 2024). Characterised solids retained crystalline phases and substantial Fe, Ca or K. One contained 48.5% SiO_2 and 23.6% CaO (Bukit et al., 2022). The coating study did not establish bulk composition of its silica-containing intermediate (Frida et al., 2024). Water extraction followed by acid precipitation produced material reported as 53.02% SiO_2, 20.765% SO_3 and 18.598% K_2O, which was tested in concrete (Olivia et al., 2024). A related mortar study did not report isolated-product composition (Olivia et al., 2023).

Other routes produced calcium-silicate paper filler (Satriawan et al., 2021) or a clinker-derived soluble material using ethylene glycol and KOH (Ismail et al., 2024). The latter source reported an oxide distribution of 53.50% SiO_2 and 43.11% K_2O. This is not an established concentration in the original aqueous product. Thermally treated laboratory EFB ash followed by milling produced crystalline nanosilica reported as 94.46% SiO_2 by energy-dispersive XRF (Agi et al., 2022). Its energy/cost estimate has an ambiguous nanomaterial-production versus ultrasound-assisted oil-recovery boundary. These routes extend the product range but require explicit product identity and process boundaries.

COMPARABILITY OF REPORTED PRODUCT QUALITY

Purity depends on the analytical basis

Reported composition values cannot be compared without identifying the sample, material stage, analytical method and normalisation basis (Figure 2). Thirty-three reports were classified by characterisation of a solid material: 15 provided bulk XRF oxide values, one elemental XRF values, 10 EDX/EDS alone (including one qualitative spectrum without a numerical value [Utama, Saputra, et al., 2018]), and seven qualitative or unreported information. Six other reports provided only ICP information on an intermediate silicate rather than bulk composition of the final mesoporous support. Nine concerned silicate/silica solution routes, including analyses of dried residues. Route classification does not mean that every percentage was measured on an aqueous-product mass basis.

Bulk-XRF values for solid products ranged from 45.13% (Novita & Idris, 2022) and 45.6% (Rahmat et al., 2021) to 96.90% (Utama et al., 2019). These are reported composition values, not a harmonised set of validated purities. The application-selected condition, highest-yield condition or full experimental range must be specified when one report contains several products (Table 1).

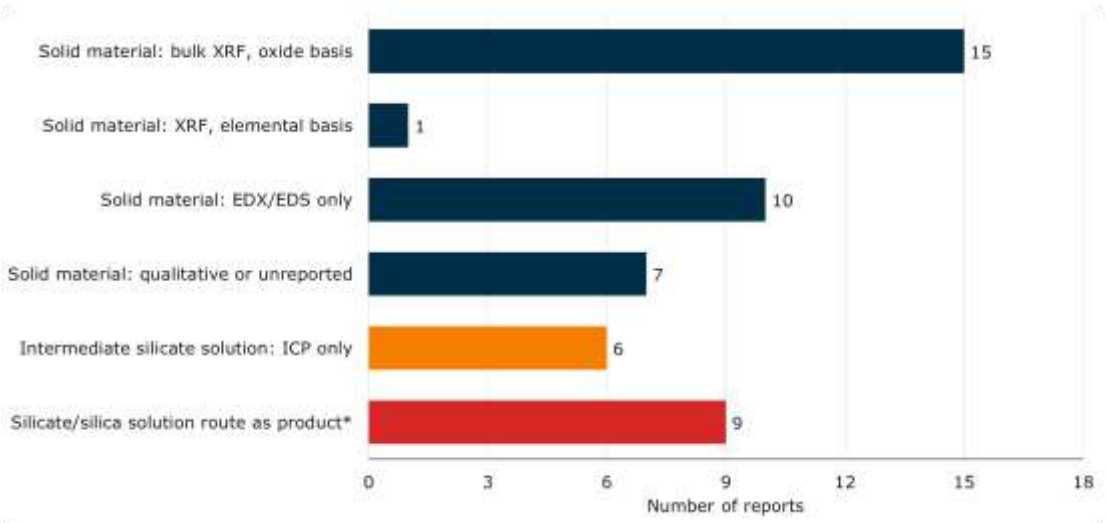

Figure 2 Material stage and analytical basis of reported characterisation in the 48 included reports. *Solution-route entries include analyses of dried residues as they do not imply directly comparable aqueous-product concentrations.

EDX or EDS can provide quantitative elemental analysis under appropriate calibration, specimen preparation and acquisition conditions (Newbury & Ritchie, 2013). However, a local powder measurement does not automatically represent bulk composition. The included reports often lacked sufficient information to establish

representativeness, standardisation, or whether reported percentages were mass-based, atomic-based or normalised to selected elements.

Elemental Si values of approximately 30.44–39.90 wt% (Mohd Sufian et al., 2026; Fynnisa et al., 2025; Kusumaningtyas et al., 2024; Sitohang et al., 2024; Utama et al., 2022) are not SiO_2 percentages. A stoichiometric conversion would provide only an oxide-equivalent estimate if all measured Si belonged to SiO_2, oxygen and other constituents were handled consistently, and the analysed material represented the bulk sample. It would not validate purity. Likewise, the 95.6% selected-element Si value (Manurung et al., 2026), 96.59% Si+O sum (Imoisili et al., 2020a) and approximately 98% claim accompanied by inconsistent Si/O proportions (Ayub et al., 2023) describe different quantities and must not share a common purity axis.

XRF also requires a stated sample state and mass basis. LOI was reported in only 12 of the 48 reports. Oxide normalisation may therefore obscure carbon, moisture or other constituents excluded from the analytical total. A normalised oxide percentage can overstate the whole-sample SiO_2 fraction when such constituents are omitted. One raw-ash composition table totals more than 100% (Olivia et al., 2024). Dried silicate residues (Lazarus et al., 2025) and incompletely specified oxide distributions (Ismail et al., 2024) cannot be compared directly with aqueous commercial silicate concentrations.

Yield is reported rarely and defined inconsistently

Fifteen reports presented a numerical value described as yield, conversion or a related extraction quantity, including one extract concentration (Table 2). Three explicitly reported product mass per ash mass (Mohd Sufian et al., 2026; Hoerudin et al., 2024; Sitohang et al., 2024). Other values concerned silica entering an extraction solution (Utama et al., 2018, 2018a), author-reported recovery relative to initial oxide (Ayub et al., 2023), reported dissolution or composition-ratio proxies (Alnahhal et al., 2023; Ghanim et al., 2025; Lazarus et al., 2025), or product volume per solvent volume (Hoerudin et al., 2025). Five values lacked a usable mass-yield definition, including the concentration reported as an extraction result (Imoisili et al., 2020a, 2020b; Novita & Idris, 2022; Satriawan et al., 2021; Utama et al., 2022). A stated or inferable denominator does not establish a valid complete recovery balance.

Where possible, Equation (1) was used only for conditional reconstructions. Hoerudin's 17.25% product-mass yield gives approximately 30.2% silica recovery if the denominator corresponds to ash containing 54.10% SiO_2 and both analyses have compatible mass bases (Hoerudin et al., 2024). The pretreatment-stage denominator remains important. For kernel-shell ash, an undefined 54.35% value could mean 54.35% recovery or approximately 92.7% if interpreted as product mass per ash mass with the reported compositions (Imoisili et al., 2020b). These are alternative interpretations, not validated efficiencies. Novita's analogous 27.8% calculation uses a feed composition cited from earlier work and is retained only as an illustration of uncertainty (Novita & Idris, 2022).

Table 2 Reported yield-related quantities and their definitions, with conditional interpretations distinguished from validated recovery

Report	Value reported	Definition given by the authors	Quantity measured / interpretation	Final-product recovery by Eq. (1)
Utama et al. (2018)	60.11%	Calculated value based on stated assumptions, not measured	Calculated extraction assuming fixed carbon	Not established
Utama et al. (2018a)	60.42 ± 0.83%	Si converted to silicate relative to Si in ash, by ICP	Extraction into solution	Not established
Ayub et al. (2023)	ca. 80 wt%	Based on initial SiO_2 content of raw POFA	Author-reported recovery; analytical	ca. 80% as claimed; not independently validated

			caveat	
Hoerudin et al. (2024)	17.25 ± 1.30%	Product mass per mass of re-ashed POFA (citric-acid leached before extraction)	Product mass / POFA mass	30.2%‡, conditional
MohdSufian et al. (2026)	17%	Product mass per ash mass	Product-mass yield	Not established
Sitohang et al. (2024)	44.6%	4.46 g silica from 10 g ash	Product-mass yield	Not established
Alnahhal et al. (2023)	54–82%	SiO_2 in silicate relative to SiO_2 in treated ash	Reported dissolution; source basis required	Not established
Ghanim et al. (2025)	44.48–65.42%	'Yield of silica' column; no formula	Composition-ratio proxy	Not established
Lazarus et al. (2025)	13.46%	Share of TPOFA SiO_2 dissolved; formula NR	Reported dissolution; balance unclear	Not established
Hoerudin et al. (2025)	12.98%	Volume of concentrated product per volume of solvent	Product volume / solvent volume	Not applicable
Utama et al. (2022)	80.01% / 81.01%	Not defined; two values in one paper	Undefined	Not established
Novita and Idris (2022)	34%	Not defined	Undefined yield; cited feed composition	27.8%‡, illustrative only
Imoisili et al. (2020b)	54.35% / 56.65%	Not defined; purity also called 'yield'	Undefined content/yield; multiple values	54.35% or 92.7%§; conditional
Imoisili et al. (2020a)	54.35%	Not defined	Undefined	Not established
Satriawan et al. (2021)	0.8770 M	Silica concentration in extract	Extract concentration, not yield	Not applicable

‡Conditional calculation only: assumes product mass/ash mass and compatible composition bases. For Hoerudin, the denominator must correspond to the ash stage represented by the reported composition; pretreatment losses are not fully balanced. Novita uses a literature-cited feed composition, not an analysis of the actual feed. §54.35% if already a recovery; 92.7% if product mass/ash mass using 96.83% product SiO_2 and 56.76% ash SiO_2. “Not established” means that the source does not support a compatible final-product mass balance.

Crystalline phases and the "amorphous" claim

Twenty reports were coded as describing an amorphous product using XRD. Other sources reported crystalline phases in acid-leached, milled, desiccant, filler or thermally treated products (Agi et al., 2022; Bukit et al., 2019, 2022; Manurung et al., 2026; Novita & Idris, 2022; Pa et al., 2016; Razak et al., 2019; Satriawan et al., 2021), and after higher-temperature calcination of templated materials (Kusumaningtyas et al., 2024; Sitohang

et al., 2024). These phase assignments are attributed to the original authors. They were not independently refined against raw diffraction data.

Hoerudin's approximately 46–51% crystallinity index is not a validated crystalline-silica mass fraction and should not be interpreted as evidence of approximately 50% crystalline silica (Hoerudin et al., 2024). Inhaled crystalline silica in the form of quartz or cristobalite is classified as carcinogenic to humans (IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2012). Only three reports were coded as discussing crystalline silica or worker-health issues (Ayub et al., 2023; MohdSufian et al., 2026; Hoerudin et al., 2024). For products intended to be handled as powders, application-specific quantitative phase analysis, particle-size information and respirable exposure assessment are needed as a phase name alone does not quantify exposure.

REPORTING COMPLETENESS

Reporting was most complete for reagent inputs and much less complete for inventories needed to assess scale-up (Figure 3). Reagent inputs were stated in 47 of 48 reports where numerical raw-ash SiO_2 values occurred in 33 and product-composition values in 28, with varying analytical bases. BET area was reported in 21, ash batch mass in 25, replicates or error bars in 18, some water-use quantities in 14, and effluent or by-product handling in seven. These frequencies represent data trends across a varied collection of reports. They do not reflect how well any individual product actually performs.

Evidence needed to assess the cost, safety and scale-up potential of silica recovery was limited. One report estimated energy use and cost, but it was unclear which processing steps the estimate covered. The reported units also lacked a consistent basis, preventing reliable comparison with other silica-production processes (Agi et al., 2022). One report measured contaminants relevant to the intended product application and compared the results with a named requirement (Hoerudin et al., 2025). Another proposed recovering reagents for reuse, but its calculation relied on an assumed recovery rate rather than experimental measurements (Utama et al., 2019). None of the included reports demonstrated a complete cycle in which extraction reagents were recovered and reused. No report provided a quantitative life-cycle assessment (LCA) of the recovery process or demonstrated production beyond laboratory scale. Although 40 reports made general economic claims, such as describing the process as low-cost, these claims did not establish economic feasibility. A techno-economic assessment would require a defined production scale and process boundary, together with quantified costs for equipment, reagents, energy, water and waste treatment.

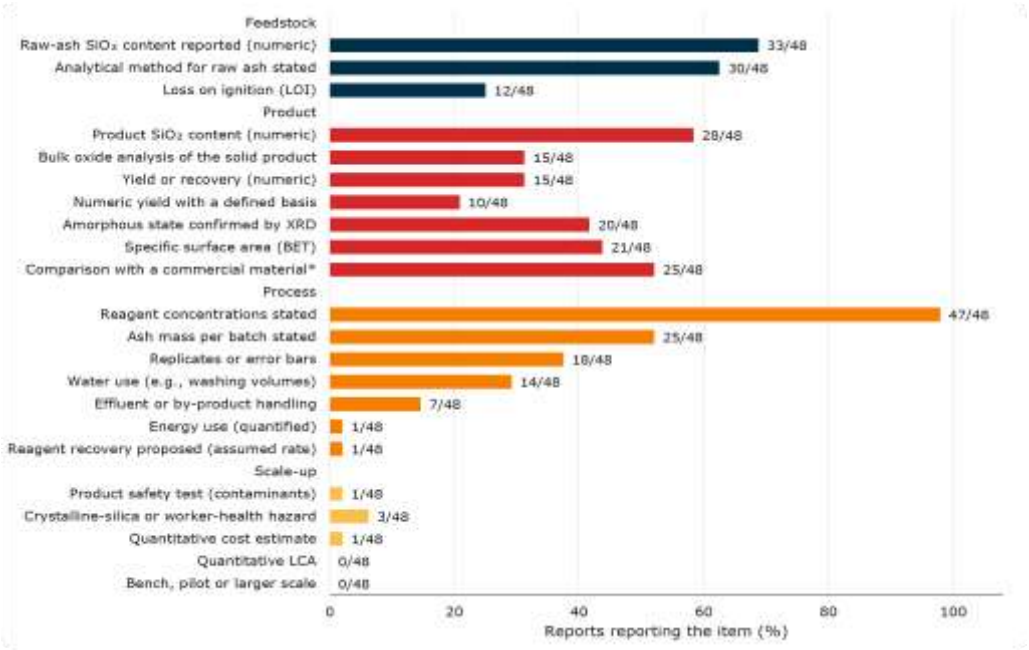

Figure 3 Frequency of 22 descriptive reporting indicators in the 48 included reports. *Commercial comparisons include published/specification values, 14 reports listed an experimental comparator.

BARRIERS TO SCALE-UP

Reagent demand, salt by-product and effluent

Silica recovery by alkaline dissolution and acid precipitation requires chemical reagents and produces salt-containing wastewater. In an idealised sodium metasilicate process, NaOH dissolves silica to form sodium silicate, and HCl then precipitates the silica:

$SiO_2 + 2NaOH \rightarrow Na_2SiO_3 + H_2O$

$Na_2SiO_3 + 2HCl \rightarrow SiO_2 + 2NaCl + H_2O$

Based on these reactions, producing 1 kg of SiO_2 requires approximately 1.33 kg of pure NaOH and 1.21 kg of pure HCl, and generates 1.95 kg of NaCl. If H_2SO_4 replaces HCl, the corresponding requirement is approximately 1.63 kg of pure H_2SO_4, with 2.36 kg of Na_2SO_4 generated. These calculations assume that the reagents are used once without recovery or reuse. They describe the chemical requirements of this specific reaction scheme rather than actual plant consumption. Actual demand may differ because of reagent recovery, different silicate compositions, reactions with other ash constituents, or the use of excess reagents.

Some studies reported substantial alkali inputs. Examples include a NaOH-to-ash mass ratio of 2:1 for fusion (Abdullah et al., 2018), a KOH-to-ash mass ratio of 3.5:1 (Ayub et al., 2023), and 500 mL of 3 M NaOH solution for every 50 g of ash (Imoisili et al., 2020a). Several processes also required repeated washing until the wash water reached neutral pH (Imoisili et al., 2020a, 2020b; Kusumaningtyas et al., 2024; Sitohang et al., 2024). This step adds to water demand and produces wastewater containing salts and dissolved substances removed from the product. However, only 14 reports provided some water-use quantities, and only seven discussed effluent handling. The available information was therefore insufficient to establish complete water balances or quantify wastewater generation.

Reagent recovery could reduce the need for fresh chemicals, but this benefit has not been demonstrated experimentally in the included reports. Utama et al. (2019) estimated that 1 kg of palm oil mill fly ash (POMFA) could produce approximately 200 g of silica. Their calculation assumed that 70% of the NaOH would be recovered, leaving a fresh NaOH requirement of approximately 83 g per kilogram of POMFA. Neither the estimated silica output nor the assumed NaOH recovery rate was experimentally verified. CO_2 precipitation and the recovery of iron oxide as a coproduct offer possible ways to integrate processing steps or obtain additional useful products (Irfan Khan et al., 2015; Utama et al., 2019). However, these approaches do not by themselves demonstrate reagent recycling. Evidence of a closed extraction-reagent loop would require the reagents to be recovered, reused in subsequent extraction cycles, and shown to maintain acceptable recovery performance..

Energy, cost and environmental assessment

Several recovery routes require heating at multiple processing stages. These include repeated calcination at 500–600 °C (Abdullah et al., 2018; Bukit et al., 2022; Hasnain et al., 2025a), fusion at 550–850 °C (Abdullah et al., 2018; Ayub et al., 2023), heated extraction and prolonged drying. These steps may contribute substantially to energy demand. However, operating temperatures and treatment times alone cannot establish how much energy a process consumes. This requires measured energy use for each processing step, related to a defined quantity of ash processed or product obtained.

Agi et al. (2022) reported a total energy use of 624.25 kWh and a cost of US$44.96/kg in a table concerning nanofluid-assisted ultrasound oil recovery. However, the accompanying discussion also refers to nanosilica preparation. It is therefore unclear whether the figures cover silica production, the subsequent oil-recovery application, or both. The cost calculation also combines entries in US$/kg with an ethanol entry in US$/gallon, without clearly showing how they were converted to a common basis. The electricity tariff was not stated. These uncertainties prevent the reported value from being used as a reliable silica-production cost or compared directly with estimates from other processes.

No included report provided a quantitative life-cycle assessment (LCA) of the silica-recovery process. Errington et al. (2023) showed that the environmental benefits of bio-derived silicon can become uncertain once processing inputs are considered. For palm-ash silica, an assessment must consider both the potential benefits and the impacts of recovery. Potential benefits include reduced ash disposal and replacement of conventional silica or silicate products. These must be evaluated alongside the impacts of reagent production, heating, water use and wastewater treatment. Where a process produces useful coproducts, the assessment must also explain how environmental impacts are divided between the silica and those coproducts. Using waste ash as a feedstock may offer environmental benefits, but the feedstock's waste origin alone does not establish that the overall process has a lower environmental impact than conventional production.

Product safety, specifications and regulation

The safety and quality requirements for recovered silica depend on its intended use. The included reports proposed or tested products for medicine-packaging desiccants (Novita & Idris, 2022), drug delivery (Imoisili et al., 2020b), textile coatings (Frida et al., 2024) and fertilisers (Hoerudin et al., 2025). These applications require different forms of assessment. Within the included reports, only the fertiliser study measured lead (Pb), cadmium (Cd), arsenic (As) and mercury (Hg) and compared the results with a named national requirement (Hoerudin et al., 2025). Measuring elemental impurities provides useful composition data, but it does not by itself establish that a product is safe for a particular application. Similarly, testing a coproduct does not establish the safety of the recovered silica, so the silica itself must be assessed separately.

Biomass ash can contain metals, and the regulatory requirements for ash-based fertilisers vary between jurisdictions (Silva et al., 2019). A product must therefore be assessed against the requirements of the country or market in which it will be used. Its performance must also be demonstrated for the intended application. For example, the chemical composition of a silicate fertiliser alone cannot establish its effectiveness, so the plant testing under relevant growing conditions is needed (Coskun et al., 2019).

Standardised test methods are available for some silica applications, including rubber compounding (International Organization for Standardization, 2022). Although some included studies compared selected product properties with published ranges (Utama et al., 2016, 2018a), these comparisons covered only part of the evidence needed to establish suitability. No included report demonstrated that its product met a complete commercial specification for the proposed use. Future studies should identify the intended application, state the relevant safety and quality requirements, and test the final product against those requirements.

Scale and feedstock variability

All 46 reports that stated their experimental scale described laboratory work. The largest reported ash quantities did not exceed 0.6 kg. Examples include 600 g used in a pretreatment batch (Hoerudin et al., 2024), 480 g used for clinker extraction (Ismail et al., 2024), and 468.2 g used for palm oil mill fly ash (POMFA) extraction (Utama et al., 2016, 2018, 2018a). These quantities describe material processed at specific stages and do not demonstrate continuous production or operation at pilot scale. Equipment capacity must also be distinguished from the amount actually processed. A large vessel, for example, does not establish a large production scale unless the study reports the batch quantity or processing rate.

Most feedstocks came from individual mills or particular collection samples, and one report explicitly stated that it used a single batch (Utama et al., 2016). The included studies did not systematically examine differences between mills, boiler types or collection seasons. Nevertheless, reported SiO_2 contents in industrial ash and clinker ranged from 27.3% to 61.6%, showing substantial variation among the feedstocks studied. Results obtained from one ash sample therefore cannot establish that a process will perform consistently with ash from other sources.

Although 18 reports included replicates or error bars, these may represent repeated tests on the same ash sample rather than tests using independently collected feedstock batches. Assessing process reliability requires trials with multiple batches from different mills and collection periods, followed by testing at larger scales. Mass balances should also track silica through pretreatment, extraction, precipitation and washing, where

applicable. This would show where losses occur and whether product quality and overall recovery remain consistent as feedstock and processing scale change.

Benchmarking against commercial alternatives

Twenty-five reports compared palm-ash products with commercial alternatives. Eleven relied on published values or specification ranges, while 14 tested a reference material within the same study (Table 3). Reference materials included commercial silica and silicate, silica fume, TEOS-derived SBA-15, Portland cement, paper fillers and liquid fertiliser. These comparisons assessed different applications and performance measures. They therefore cannot be combined into a single ranking of palm-ash products against commercial alternatives.

Some studies reported results close to those of their reference materials. Examples include methane conversions of 91.4% versus 92.1% (Chong et al., 2019) and mortar strengths of 51 versus 52 MPa (Alnahhal et al., 2023). Ghanim et al. (2025) also reported strengths of 58.9 versus 62.9 MPa, indicating useful laboratory performance for the formulation tested. However, similar numerical values alone do not establish equivalent performance. Such a conclusion requires an appropriate comparison that accounts for experimental variability and defines an acceptable difference between the products.

Comparisons must also be interpreted within their experimental conditions. A higher surface area or SiO_2 content does not necessarily mean that a product performs better in its intended application. Hoerudin et al. (2024) compared selected properties rather than demonstrating overall commercial suitability. Lazarus et al. (2025) tested a 50:50 hybrid activator, so the results cannot be attributed to the recovered silicate alone. Cheng's selected conversion values were obtained under different operating conditions, which limits direct comparison (Cheng et al., 2020).

Other findings were mixed or difficult to interpret. Olivia's concrete and mortar studies reported different outcomes when palm-ash silica was compared with silica fume (Olivia et al., 2023, 2024). In Sekar's report, conflicting results in the text and table prevented a reliable conclusion about performance relative to the commercial control (Sekar & Arunasankar, 2026). Table 3 therefore presents each reported comparison together with its test conditions and interpretation limits. It does not classify products simply as having "matched" or "exceeded" commercial performance..

Table 3 In-house experimental comparisons between palm-ash products and commercial references (n = 14)

Report	Product and use	Comparator (in-house)	Metric	Reported observation / comparison limit
Hoerudin et al. (2024)	Precipitated silica	Commercial precipitated silica	SiO_2, BET	Higher reported SiO_2 and BET values; selected properties only (94.68 vs 94.00%; 390.80 vs 137.59 m^2/g)
Abdullah et al. (2018)	Ni/SBA-15, dry reforming	TEOS-derived Ni/SBA-15	CH_4 and CO_2 conversion	Lower CH_4 conversion (TEOS 31.5% higher); CO_2 comparable; BET 515 vs 473 m^2/g
Chong et al. (2019)	Ni/SBA-15, dry reforming	Commercial Na_2SiO_3-derived catalyst	CH_4 conversion	Numerically close methane conversion (91.4 vs 92.1%); equivalence not established
Razak et al. (2019b)	SBA-15, dry reforming	Commercial Na_2SiO_3-derived SBA-15	BET, conversion	Lower BET (524.74 vs 598.67 m^2/g); slightly higher conversion
Cheng et al. (2020)	Clinker SBA-15, ethanol	Commercial Na_2SiO_3-derived	Ethanol conversion	Favourable catalytic results; 73.33% and 28.96% were obtained under different

	dehydration	SBA-15		operating conditions
Olivia et al. (2024)	Precipitated silica in concrete	Silica fume	28-d strength gain	Higher reported 28-day strength gain (+38.11 vs +23.34%); formulation-specific
Olivia et al. (2023)	Precipitated silica in mortar	Silica fume	Compressive strength	Lower (by ~12–21%)
Alnahhal et al. (2023)	Silicate activator	Commercial sodium silicate	28-d strength	Numerically close 28-day strengths (51 vs 52 MPa); formulation-specific
Ghanim et al. (2025)	Silicate activator	Commercial sodium silicate	56-d strength	Lower (58.9 vs 62.9 MPa)
Lazarus et al. (2025)	Silicate activator (50:50 blend)	Commercial sodium silicate	28-d strength	Favourable hybrid-blend result; only 50:50 ash-derived/commercial silicate tested
Sekar and Arunasankar (2026)	Silicate activator	Commercial sodium silicate	28-d strength	Unresolved: text control 39.5 MPa versus table control 45.8 MPa
Kunchariya-kun et al. (2023)	Nanosilica in belite cement	Ordinary Portland cement	Compressive strength	Lower
Satriawan et al. (2021)	$CaSiO_3$ paper filler	Commercial PCC and GCC	Optical and strength indices	Mixed (higher brightness, opacity, bulk; lower tensile, tearing)
Hoerudin et al. (2025)	K silicate fertiliser	Commercial liquid silica fertiliser	Available SiO_2	Slightly lower (18.50 vs 20.71%)

Regional context

Malaysia and Indonesia were the main sources of feedstock in the included reports. Eighteen reports used Malaysian material and 13 used Indonesian material, while nine did not specify its origin. Few reports identified industrial or government partners. Examples included an inspection company (Novita & Idris, 2022), agricultural funding and government organisations (Hoerudin et al., 2025), and an ash supplier (Hasnain et al., 2025a). However, none demonstrated a pilot recovery process jointly designed with a palm oil mill. The reported involvement of these organisations therefore does not establish that the processes were developed or tested for routine mill operations.

Some reports discussed local conditions, but none combined measured process inputs and outputs with an assessment of ash supply, transport requirements and regional demand for a clearly defined product grade. This information is needed to determine whether a recovery process could operate practically in the Southeast Asian palm oil sector. Such an assessment should establish how much suitable ash is available, how consistently it can be supplied, where processing would take place, and which customers could use the resulting product. Linking these factors with measured reagent, energy, water and waste quantities would provide a stronger basis for assessing commercial deployment.

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MINIMUM REPORTING CHECKLIST

Table 4 proposes 14 reporting items to improve the clarity and comparability of future studies. The items are grouped by domain, and authors should state which apply to their product and process. Different products require different measurements. For example, solid powders require appropriate composition and phase characterisation, while liquid silicates require solution-composition measurements. Application tests should reflect the intended use of the final product.

The main recommendation is to define the process boundary and calculate silica recovery using a consistent mass balance. Authors should identify where the assessment starts and ends, such as from untreated ash to the final dried product or from pretreated ash to an extraction solution. For an isolated solid product, silica recovery can be calculated as:

$$Y(SiO_2) = [m(product) \times w(SiO_2, product)] / [m(ash) \times w(SiO_2, ash)] \times 100\% \quad (1)$$

Here m is mass and w represents the SiO_2 mass fraction. The numerator gives the mass of SiO_2 in the recovered product, while the denominator gives the mass of SiO_2 in the starting ash. Both must be calculated on a compatible basis. For example, a dry product mass must be paired with its dry-basis composition. Authors should report moisture content, loss on ignition (LOI), and whether oxide percentages were normalised to a total of 100%.

The starting material must also be clearly identified as untreated ash or ash collected after a specified pretreatment step. Recovery calculated from pretreated ash describes only the subsequent processing stages. If overall recovery from untreated ash is claimed, silica losses during pretreatment must also be included. Any silicon added through reagents or modifiers must be accounted for separately so that it is not incorrectly counted as silicon recovered from the ash.

For liquid products or extraction intermediates, the recovered silicon mass can be calculated by multiplying the measured solution mass by its silicon mass fraction, or the measured solution volume by its silicon concentration. The feed and product must use the same analytical basis. Elemental Si in a solution, for example, must not be compared directly with SiO_2 in the ash without an appropriate conversion.

Authors should report dissolution efficiency, precipitation-stage recovery and overall recovery separately because each describes a different part of the process. Product-mass yield should also be reported separately, as the mass of product obtained does not by itself show how much of the original silica was recovered. Where possible, studies should include analytical uncertainty, the number of replicates, and the silicon remaining in solid residues and liquid effluents. These measurements help account for losses and assess whether the mass balance is complete..

Table 4 Minimum reporting checklist for studies of silica recovery from palm oil ash

Domain	**Minimum item, where applicable**	**Why it matters (finding in this review)**
Feedstock	Mill, boiler type and fuel mix; sampling date and number of batches	Source and batch variation are insufficiently characterised
Feedstock	Bulk oxide composition (XRF method: bead or pellet, calibration) with LOI	LOI reported in 12/48
Feedstock	Crystalline phases by XRD, quantified where possible	Quartz and cristobalite carried into products
Process	Ash mass per batch; reagent amounts as mol per mol SiO_2; solid/liquid ratio; temperature and time	Batch mass stated in 25/48

Process	Washing water volume; effluent composition and handling; salt by-product mass	Water use 14/48; effluent 7/48
Process	Energy input for each thermal step; reagent recovery tested, not assumed	Energy estimated in one report; reagent recovery assumed in one and tested in none
Product	Solid products: bulk SiO_2/Si analysis with explicit sample state, oxide normalisation and LOI; major residual constituents. Liquid products: analyte concentration, water/solids content and density.	Local elemental values and dried residues are not equivalent to bulk or aqueous-product composition
Product	Powders: crystalline-phase identification and quantification where relevant; particle-size distribution and respirable exposure information	Health hazard mentioned in 3/48
Product	Where porosity is claimed: adsorption/desorption isotherms, suitable pore-size analysis, pore volume and specific surface area	Mesoporosity depends on pore size; low BET area alone does not invalidate it
Yield	Stage-resolved extraction, precipitation and overall recovery balances; product-mass yield separately; explicit original/pretreated feed denominator	Solution extraction, composition ratios and volumetric yield were conflated with final recovery
Quality	Replicates (n) with dispersion; consistency of abstract, text and tables	Replicates in 18/48; frequent inconsistencies
Benchmark	Commercial comparator for the same function under matched conditions; uncertainty and blend proportions stated	Some comparison values concern different conditions or partial substitution
Safety	Application-relevant contaminants (e.g. Pb, Cd, As, Hg) against a named standard	Tested in 1/48
Scale and economics	Actual batch throughput; measured mass/energy inventories; cost functional unit, tariff and system boundary; LCA boundary and coproduct allocation	One boundary-ambiguous cost/energy estimate; no quantitative process LCA or recovery beyond laboratory scale

LIMITATIONS OF THIS REVIEW

This review searched two databases and assessed only the peer-reviewed reports that could be retrieved. Relevant evidence from patents, theses, other grey literature and industrial practice may therefore be missing. The eligibility decisions introduce another limitation. Reports that only characterised calcined ash were excluded, whereas reports that thermally treated ash and then processed it into a nanoscale product were included. Excluding studies that only characterize raw calcined ash ensures that the scope remains strictly confined to the production, properties, and applications of advanced, value-added nanostructures. Comparisons were also limited by inconsistent feedstock names, unclear sample states, different yield definitions and contradictions within some publications. Recovery calculations based on stated assumptions can illustrate possible interpretations, but they cannot replace missing measurements or establish a complete mass balance.

No formal framework was used to rate the certainty of the evidence, and no validated risk-of-bias tool was applied. The appraisal instead examined whether reporting was clear, internally consistent and sufficiently detailed to support comparisons. Complete reporting was not treated as proof that an experiment was valid.

Similarly, shared authorship and repeated numerical values were recorded, but neither could establish how many independent experiments had been conducted.

Finally, findings about the absence of pilot-scale work, demonstrated reagent-recovery loops and quantitative life-cycle assessments apply only to the retrieved reports included in this review. They do not establish that such work is absent from the wider literature or industrial practice.

CONCLUSIONS

The included reports show that oil-palm combustion ash can be processed into silica-containing solids and silicate solutions at laboratory scale. Selected studies using alkaline extraction and precipitation reported approximately 95–97% SiO_2 by XRF. Some recovered silicate activators also produced mortar strengths close to those of commercial controls (Alnahhal et al., 2023; Ghanim et al., 2025). These results demonstrate technical potential under the conditions tested, but do not establish that the products consistently meet commercial specifications.

Direct comparison between studies remains difficult because feedstocks, processing conditions, sample types and analytical methods differ. Elemental Si measured by EDX, selected-element totals, dried-residue compositions and bulk oxide percentages describe different quantities and should not be treated as equivalent measures of purity. Likewise, silica dissolved into an extraction solution, silica recovered during precipitation and the mass of the final product represent different process outcomes. Overlapping datasets also mean that the number of reports cannot be assumed to represent the number of independent experiments. Unresolved screening decisions and unavailable reports further limit the review's coverage.

Evidence supporting commercial production remains limited. No included report experimentally demonstrated recovery and reuse of extraction reagents. The only energy/cost estimate had an unclear process boundary, and only one report tested application-specific contaminants against a named requirement. None provided a quantitative process life-cycle assessment or demonstrated recovery beyond laboratory scale. The available evidence therefore does not establish commercial readiness or economic and environmental advantages over conventional production.

Future studies should use clearly defined analytical bases, measure bulk composition and relevant phases, and track silica through each processing stage using complete mass balances. Process reliability should be tested using independently collected ash batches from different mills, followed by larger trials that measure reagent, energy and water use, as well as waste generation. Final products should be tested against application-specific commercial requirements, supported by techno-economic and life-cycle assessments. The minimum reporting checklist in Table 4 provides a framework for generating the evidence needed to assess practical deployment.

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