Review

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The Impact of Calcination Temperature on the Chemical Composition, Physical Properties and Pozzolanic Performance of Agro-Waste Ashes

Augustine Akumasi *, Joshua Ayarkwa, Alex Acheampong and Godwin K. K. Acquah

Department of Construction Technology and Management, College of Art and Built Environment, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

* Correspondence: akumasiaugur@yahoo.com

Abstract

The pressing need to minimize cement-related CO_2 emissions attracted the search for agricultural waste ashes as supplementary cementitious materials (SCMs). Agro-waste ashes, rich in silica and alumina, are promising cementitious materials. However, prior researchers reported inconsistent chemical compositions and physical properties due to differences in calcination methods. This systematical review proofed the impact of calcination temperature on the chemical composition, physical properties and pozzolanic performance of agricultural waste ashes. Systematic Literature Review (SLR) following PRISMA protocols, with published articles retrieved from Scopus, Web of Science, Wiley Online Library, and Google Scholar (2014–2025) was used for the study. Using keywords, 524 published articles were first identified; after screening and eminence evaluations, 50 articles met the inclusion criteria. Data was obtained mainly on calcination methods, chemical compositions, physial properties and compliance with standards such as GS 1118 (2016) EN 197-1 (2011) and SANS 50197-1. Comparative analysis disclosed constant deficiencies in CaO (0.91–25.80%) and extreme SiO_2 (40–63%) and Al_2O_3 (10–42%) contents, particularly with open-air burning. The findings emphasized 600–700°C for 90–120 minutes as the best manufacturing window for standard-conformity of ashes derived from agro-waste materials. This review highlighted the importance of controlled calcination, identified research gaps, and provided evidence-based principles for manufacturing SCMs in construction.

Keywords: agro-waste ashes; calcination temperature; chemical compositions

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1. Introduction

Cement production contributes largely to the growth of the construction industry globally. Ordinary Portland Cement (OPC) manufacturing does not only emits close to 8% of carbon dioxide (CO_2) to the environment but also leads to higher energy consumption worldwide [1,2]. As a result, the interest of researchers is now focused on investigating into agricultural waste materials that can sustainably replace cement applications to reduce these environmental challenges. According to Oyebisi et al. [3], the acceptable method worldwide is the utilization of agro-waste materials as a partial replacement of cement. Importantly, the use of agricultural waste as supplementary cementitious material (SCMs) in the construction industry will minimize the waste deposits on agricultural farms and increase material sustainability.

Cashew nut shell, corn cobs, coconut shells and others are some of those major agricultural residues that are rich in silica (SiO_2) and alumina (Al_2O_3) content, and key for pozzolanic activity [3]. It was reported that cashew nut shell ash influence greatly the durability and physical properties and performance of compress earth [4]. However, prior studies continue to report different results of chemical compositions with deficiencies of pozzolanic reactivity.

Variations and deficiencies of key chemical composition (CaO, SiO_2 and Al_2O_3) are due to noncompliance with standard calcination protocols during the manufacturing of agricultural waste ashes [5–7]. In most reports, attentions are on calcination temperature and its impact on chemical compositions ignoring the role physical properties play in the agro-waste ashes. Differences between open-air and furnace burning have been reported to cause inconsistencies in fineness, moisture content, and specific gravity, thus affecting pozzolanic effectiveness [3,8]. Conversely, a methodological establishment of such findings has been missing, giving clear knowledge gaps in comprehending ways in which these properties meet industry standards [8].

Neville [9] reported that calcination temperature is a key factor determining the retention of the chemical composition that directly impact positively the materials' physical characteristics since, it involves the process of converting silica and alumina into their amorphous forms. Calcination below the required temperature leads to incomplete combustion and calcining beyond the recommended temperature eventually consumes the pozzolanic reactivity index [9]. Although, experimental studies on manufacturing agricultural waste ashes as SCMs is on a rise, there is paucity of information on systematic review associated with calcination conditions particularly with the chemical composition as well as physical properties and pozzolanic suitability of agro-waste ashes following industry cement standards.

Literature shows that the chemical composition of CNSA among studies varied across geographical locations [7]. Notwithstanding factors such as soil formation of the different locations, cashew types and weather conditions that contributed to the differences in chemical compositions, calcination conditions (burning method and temperature and time control) play a very vital role in the chemical oxide formation of the CNSA [3,4].

The current study reports this critical gap adopting a systematic literature review (SLR) carried out in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocols. The objectives were: (i) to synthesize reported chemical compositions and physical properties of ashes manufactured from agro-waste materials using different calcination approaches, (ii) to evaluate researchers' compliance with industry standards GS 1118 [11] and EN 196-7 [10] and (iii) to determine the optimum calcination temperature for manufacturing ashes from agro-waste materials that retains chemical oxides and physical properties inside industry standards' recommendations. By incorporating separate findings into an organized analysis, the review adds evidence-based procedures which can aid researchers, policymakers, and industry stakeholders in promoting the application of agro-waste ashes as sustainable SCMs in construction.

2. Literature Review

Reports on the use of agricultural waste ashes as supplementary cementitious materials continue to emphasize on the possibility of utilizing these materials to minimizes carbon footprint and environmental degradation through cement manufacturing. Aprianti [12] and Chusilp and Kiattikomol [13] indicated that agro-waste ashes like rice husk ash, sugarcane bagasse ash, and palm oil fuel ash had been broadly examined and are recommended for their pozzolanic reactivity. Assessing the impact of calcination temperature on the chemical composition, physical properties and pozzolanic performance underscores the critical role of thermal processing, especially burning temperature, in converting agro-waste materials into active ashes for use as sustainable SCMs.

Literature has revealed the importance of Cashew Nut Shell Ash (CNSA), Rice Husk Ash (RHA), Sugarcane Bagasse Ash (SCBA), Palm Oil Fuel Ash (POFA) etc. as SCMs in the construction industry in recent times [2–4]. These materials contain sufficient quantities of silica (SiO_2) and alumina (Al_2O_3) contents hence, their application in lateritic blocks, mortar and concrete as partial replacement of cement [3,4]. Unfortunately, prior researchers continue to report vast difference in chemical compositions across both manufacturing methods (controlled furnace or open-air burning) deployed. Some researchers recorded positive improvement of compressive strength and durability properties of compressed earth blocks with CNSA, RHA, SCBA addition, others recorded deficiencies of these making them inappropriate for use as SCMs in construction [2,13,14]. These inconsistencies are basically linked to differences in calcination protocols [5–7].

Calcination is the process of burning the raw materials of cement at controlled temperatures to produce ash with required chemical and mineralogical properties. [5–7]. Fernandez et al. [14] and Neville [9] further explained that in cement production, calcination takes place at around 1450°C, producing consistent oxides in conformity with standards like GS 1118 [10] and EN 196-7 [11]. In contrast, Rosseira, et al. [5] and Sata et al. [7] reported that since, agricultural waste materials are comparatively less heavy or hard, they need to be manufactured at temperature within the range of 600–700°C, for effective activation of pozzolanic phases. Manufacturing ash from agro-waste materials above 700^{o}C often result in poor chemical composition of the material [5,67].

Manufacturing ashes from agro-waste materials in accordance with industry conditions are often ignored by researchers. Studies have adopted calcination temperatures varying from 600°C to 800°C and beyond, with durations over 5 to 7 hours [5–7]. Such discrepancies clearly show wider differences in chemical compositions, especially in CaO, SiO_2, Al_2O_3, and Fe_2O_3 contents. Researches confirmed that 600–700°C for about 90–120 minutes gives the maximum and acceptable chemical compositions [5,6,15]. However, most studies continue to report results outside these standards [13].

On the other hand, studies authenticated that the physical properties of pozzolanic materials are role players in establishing their compatibility with cement and their effects on hydration and setting characteristics [16]. Fineness, for example, influences the surface area of the material that offers for reaction and the amount of strength development, whereas specific gravity influences its workability [17]. Equally, the soundness and consistency of the ash impact volumetric stability and durability of a pozzolanic material [18]. Notwithstanding these well-established impacts, most studies on agro-waste ashes gave little attention to standardized evaluation of such factors against industrial standards like as ASTM C204 [19], BS EN 196-3 [20], ASTM C1702-09 [21], BS EN 196-6 [22], and BIS IS 4031-P2 [23]. This dearth of standardized comparison poses challenges to assess the ashes' full appropriateness as a cement replacement.

Hence, a systematic review focusing on both the chemical oxide compositions and physical properties of agro-waste ashes is important to strengthen reported findings, ascertain consistency across all reported findings, and benchmark their maximum utilization as appropriate SCMs.

Figure 1 depicts the comparative manufacturing processes of Ordinary Portland Cement (OPC) and agro-waste ashes, emphasizing the variations in calcination temperatures and the outcomes of physical and chemical properties. This framework underscores reasons for which rigorous methodological protocols are important if agricultural materials should be applicable as a SCMs in the construction industry.

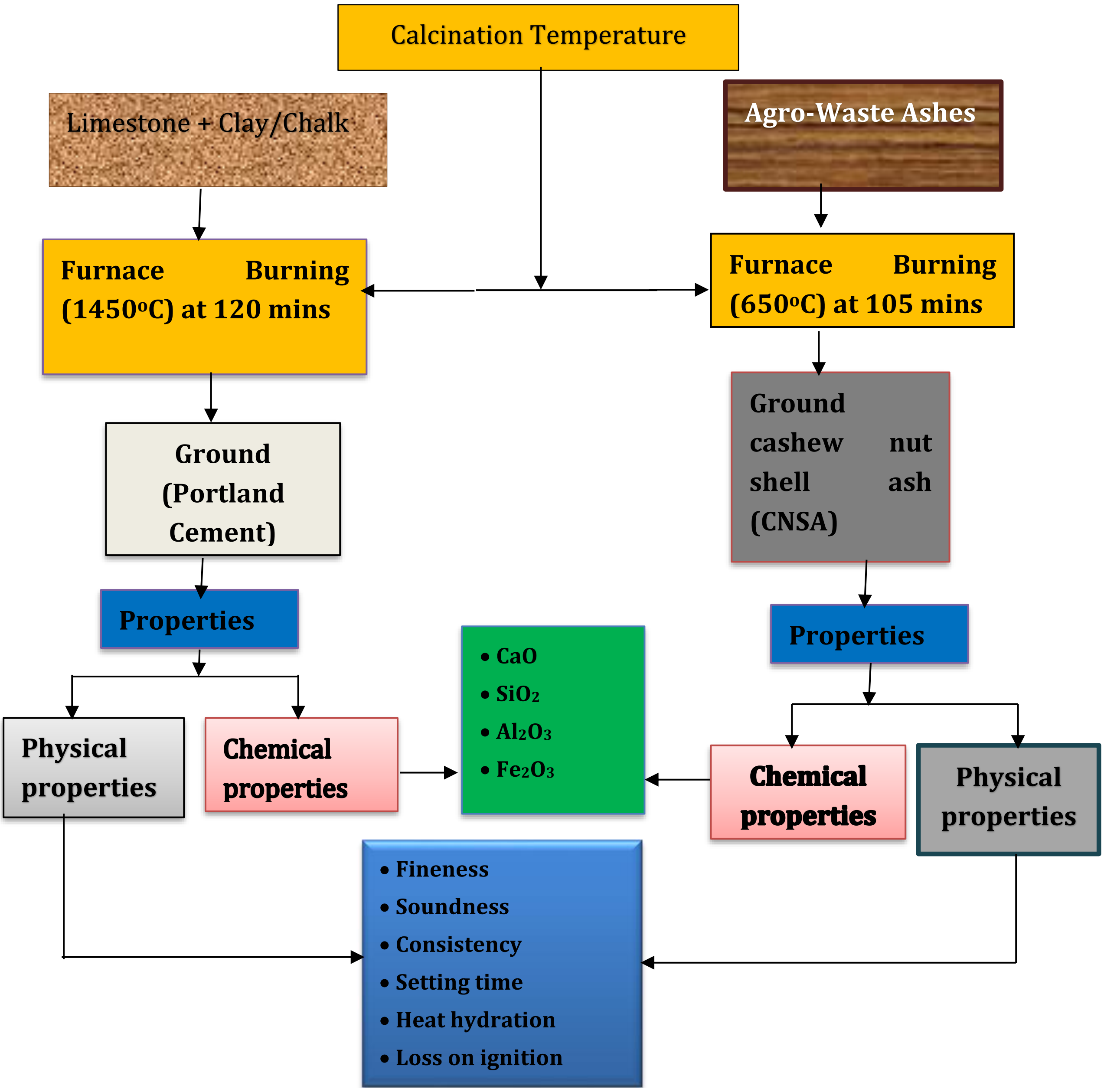

Figure 1 Manufacturing Process of Cement and CNSA Source: Author's Construct

3. Methodology

In this study, Systematic Literature Review (SLR) was adopted to evaluate the effect of calcination temperature on the chemical composition, physical properties and pozzolanic performance of ashes produced from agricultural waste materials. The choice of the SLR approach was based on Centobelli et al.'s [24] report that S.LR gives transparent, replicable, and structured procedures which improve the validity and reliability of findings. To make sure the search was rigorous, the review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standards as used by Page et al. [25] who summarized the phases into identification, screening, eligibility, and inclusion/exclusion.

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3.1. Data Collection and Search Techniques

The study obtained published articles from the following databases Scopus, Web of Science (WoS), Wiley Online Library (WOL), and Google Scholar. These databases were used because, according to Ograh et al. [26] they are globally accepted for their broad retrieval of reliable publications in construction and materials science. The exploration was narrowed to studies published in English from 2014 to 2025. Search strings pooled common terms for construction materials with particular references to agro-waste/agricultural waste materials and calcination temperature. The search keywords used were:

- "concrete" OR "blocks" OR "bricks" OR "laterite" OR "stabilization"
- combined with "agro-waste materials" OR "agricultural waste materials" OR "compressed earth bricks" OR "sandcrete blocks" OR "stabilized with CNSA"

Boolean operators and truncations were used to broaden the scope while minimizing irrelevant results.

3.2. Inclusion and Exclusion Criteria

Published papers were included in this study only if the:

1. Research was conducted with the use of agro-waste ashes in concrete, mortar, soil/earth/laterite blocks, or compressed earth bricks.
2. Results were obtained from either controlled furnace or open-air burning method.
3. Articles were peer-reviewed, full-text journal articles, published in English.

Published articles were excluded from the study if they were:

1. Conference papers, book chapters, or non-peer-reviewed articles.
2. Concentrated on non-construction uses of agricultural materials ashes.
3. Non-English or full text were inaccessible.

3.3. Screening and Selection Process

The first search retrieved 520 published articles (Scopus = 309; WOL = 119; WoS = 53; Google Scholar = 39). After eliminating 108 duplicates, 412 articles remained. Title and keyword screening removed 301 papers, whereas abstract and full-text screening eliminated 61 articles which did not meet the inclusion conditions. Therefore, the total number of published papers retained for final analysis were 50. More so, out of the 50 published papers, 14 papers reported results of chemical composition of CNSA while 36 papers reported results of chemical compositions of other agro-waste ashes.

Although the final 50 published articles were relatively few compared with the first pool, it reflected the paucity of research publications on the calcination of agro-waste ashes and emphasizes the research gap in this research domain. The PRISMA process is shown in Figure 2.1.

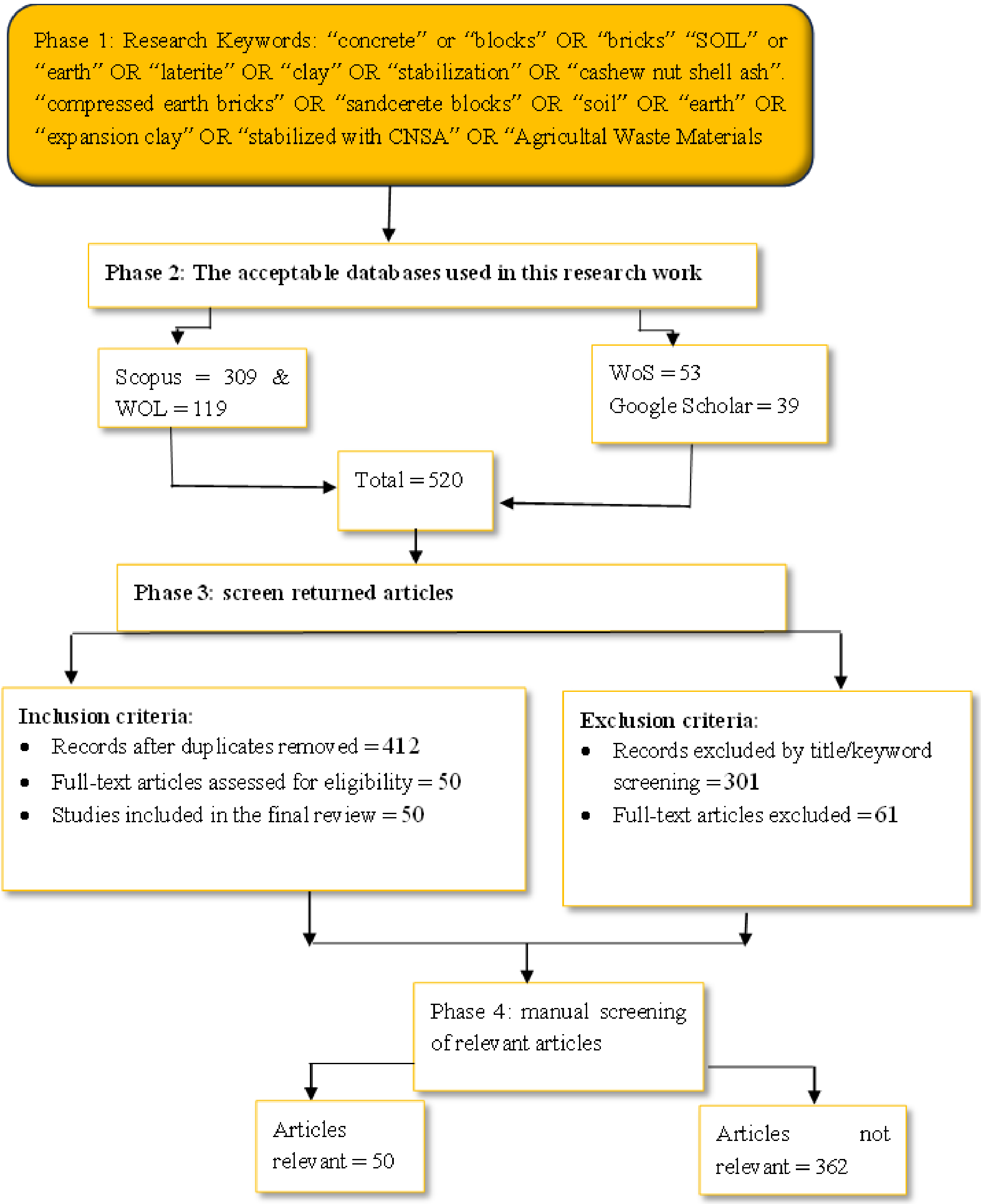

Figure 2.1 Summary of PRISMA Protocols Observed Via Database
Source: Page et al. [17]

3.4. Quality and Bias Assessment

To improve reliability, the methodological thoroughness of every published paper that was included was evaluated following the adapted criteria from McCarthy and Dyer [27]:

- Transparency of calcination method reported (temperature, duration, process).
- Full chemical composition data reported (major oxides and LOI).
- Clarity of experimental investigation (sample preparation, control conditions).

Published articles without important data (e.g., missing chemical compositions) were eliminated at the full-text screening phase.

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3.5. Retrieving and Gathering Data

Data were retrieved from the final 50 published articles using an organized format. Major variables used were:

- Calcination temperature and duratio[10,11,28n.
- Chemical oxides reported (CaO, SiO_2, Al_2O_3, Fe_2O_3, SO_3, MgO, Na_2O, and LOI).
- Compliance of values of chemical compositions with industry standards [10,11,28].
- Physical parameters – for instance fineness, specific gravity, setting time, consistency, soundness, heat of hydration, loss on ignition (LOI), colour, and moisture content.
- Conformity of physical property values with industry standards like BS as ASTM C204 [19], BS EN 196-3 [20], ASTM C1702-09 [21], BS EN 196-6 [22], and BIS IS 4031-P2 [23].

3.6. Author Affiliations and Country of Origin.

The data obtained from published articles were subjected to comparative analysis. Chemical compositions were benchmarked against industry standard threshold, and situations were analyzed among calcination ranges (600°C, 600–700°C, and >700°C) and durations (90 minutes, 90–120 minutes, >120 minutes). As data allowed, cross-study relationships were found, emphasizing consistencies and differences. Descriptive statistics and tabular comparative analysis were carried out to show oxide variations, whereas thematic analysis was utilized to explain methodological contrasts (e.g., furnace vs. open-air burning). Table 1 indicates the authors, their affiliated institutions, and countries, which emphasizes the geographical distribution of research efforts on agro-waste ashes in construction.

Table 1. Authors, their Affiliated Institutions, and Countries.

№	Author	Affiliate Institution	Country
1	Korankye and Danso [29]	Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development	Ghana
2	Oyesibi et al. [3]	Covenant University, Ota	Nigeria
3	Oyesibi et al. [30]	Covenant University, Ota	Nigeria
4	Oyesibi et al. [31]	Covenant University, Ota	Nigeria
5	Sule and Ehikwe [32]	Edo State University Uzairue	Nigeria
6	Tantri et al.[33]	Manipal Institute of Technology, MAHE	India
7	Tantri et al. [34]	Manipal Institute of Technology, MAHE	India
8	Sekunowo et al. [35]	University of Lagos	Nigeria
9	Kareem et al. [36]	Osun State University	Nigeria
10	Manjunath et al. [37]	Engineering institutions (multi-institutional)	India
11	Mendu nd Pannem [38]	VIT University	India
12	Thirumurugan et al. [39]	FET College of Engineering	India
13	Pandi and Ganesan [40]	Sardar Raja College of Engineering	India
14	Tom and Jose [41]	Noorul Islam Centre for Higher Education	India
15	Odeyemi et al. [42]	Federal University of Technology	Nigeria
16	Ainomugisha et al. [43]	Makerere University	Uganda
17	Umar and Musa [44]	Nigerian university (Engineering)	Nigeria
18	Alaneme [45]	ederal University of Technology	Nigeria
19	Gunduz and Kalkan [46]	Pamukkale University	Turkey
20	Pushpakumara and Mendis [47]	University of Peradeniya	Sri Lanka

21	Arel and Aydin [48]	Karadeniz Technical University	Turkey
22	Ghazzawi et al. [49]	Beirut Arab University	Lebanon
23	Singh et al. [50]	Indian Institute of Technology	India
24	Jamwal et al. [51]	Indian Institute of Technology	India
25	Nagarajan et al. [52]	Anna University	India
26	Sathiparan [53]	University of Jaffna	Sri Lanka
27	Al-Hokabi et al. [54]	Saudi Arabian University	Saudi Arabia
28	Fernando et al.[55]	Sri Lankan university	Sri Lanka
29	Ondego et al. [56]	University of Nairobi	Kenya
30	Oladele et al. [57]	Obafemi Awolowo University	Nigeria
31	Salim et al. [58]	Jomo Kenyatta University of Agriculture and Technology	Kenya
32	Sharma et al. [59]	Indian Institute of Technology	India
33	Aboubacar and Alphonse [60]	Université d'Abomey-Calavi	Benin
34	Adetoya et al. [61]	Nigerian University (Engineering)	Nigeria
35	Hasan et al.[62]	Bangladeshi University	Bangladesh
36	Al-Hokabi et al. [54]	Middle East Engineering Institution	Saudi Arabia
37	Olaiya et al. [63]	Nigerian University	Nigeria
38	Kalasur et al. [64]	Indian Engineering Institution	India
39	Bheel et al. [65]	International collaborative institutions	Pakistan
40	Yaw et al. [66]	University of Ghana	Ghana
41	Anagonou et al. [67]	Engineering Institution	India
42	Mendu and Pannem [38]	VIT University	India
43	Fernando et al. [55]	University-based Engineering Faculty	Sri Lanka
44	Ondego et al. [56]	Kenyan University	Kenya
45	Aboubacar et al. [60]	Beninese University	Benin
46	Singh et al. [50]	Indian Technical University	India
47	Jamwal et al.[51]	Indian Technical University	India
48	Gunduz and Kalkan [46]	Turkish University	Turkey
49	Arel and Aydin [48]	Turkish University	Turkey
50	Pushpakumara et al. [47]	Sri Lankan University	Sri Lanka

Source: Author's Construct

The results in Table 1 indicate that Nigeria and India remained the top countries in publication showing the best research results in agro-wastes ashes' investigation. Ghana, Sri Lanka, Turkey and Kenya make significant contributions while Benin, Uganda, Bangladesh, Saudi Arabia and Lebanon give less attention to research on agro-waste ashes in the construction industry. Across studies, most contributions are university-based indicating that research in this aspect is purely academic. The irregular geographical distribution as illustrated in Table 1 informs that there is the need for global collaboration to validate findings in different agriculture and construction domain.

3.7.1. Year of Publication

The chosen publications covered the period 2014 to 2025, with publication occurrence differing across years. Figure 2.2 shows the distribution of publications by year.

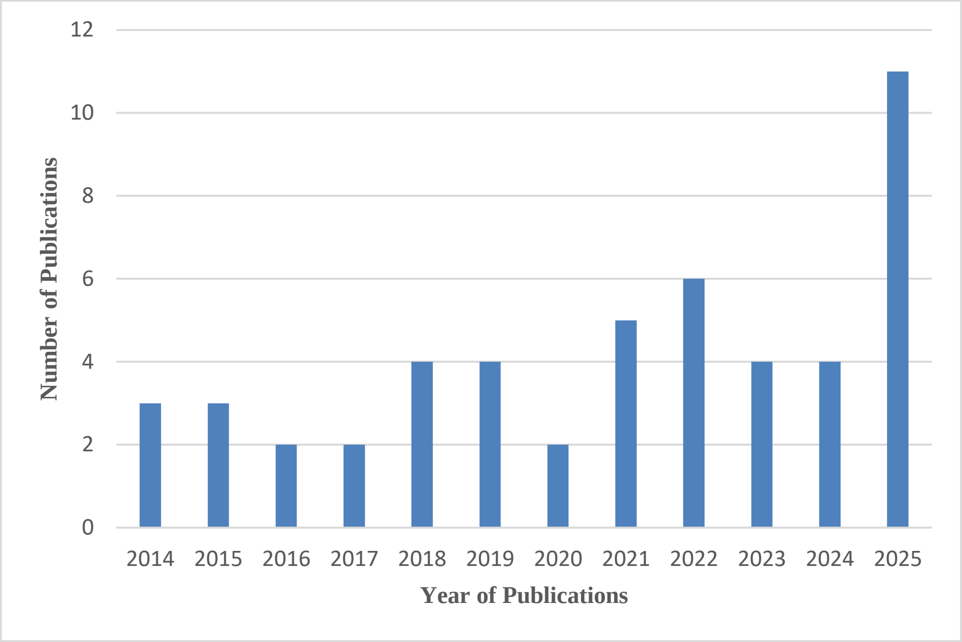

Figure 2. 2 Distribution of Publications by Year Source: Author's Construct.

As shown in Figure 2.2, research pursuit in this domain is on a rise after 2020, with a significant increase in 2022 and 2025, currently showing scholarly attention on agro-waste ashes as SCMs.

4. Results and Discussion

The geographical distribution of articles published yearly explains a significant upsurge of outcomes of research on agro-waste ashes especially from 2021 to 2025 while little experimental research was conducted in 2016, 2017 and 2020.

It can be argued that the increase in research on agro-waste ashes from 2018 – 2020 could be attributed to the world-wide alertness of greenhouse gas emanating from cement manufacturing industries. The optimum rise of publications made between 2021 and 2022 clearly depicts maximum efforts through technology to discover materials' properties and maximize policy and academic importance on circular economy and profit gain from agricultural wastes.

The publication of articles increased in 2025 highlights the importance of practical application, experimental investigations and encouraging the uses of agro-waste materials as SCMs. Studies are shifting from feasibility assessment to more practicable and performance-based research. This shows the importance of experimental investigations highlighting the role agro-waste ashes play as sustainable SCMs in the construction industry.

4.1. Standards of Cement Composition and Comparison with Agro-Waste Ashes

Table 2 summarizes the globally accepted chemical composition standards for Ordinary Portland Cement (OPC), as specified by GS 1118 [10], SANS 50197-1 [28], and EN 196-7 [11]. The standards are benchmarks for manufacturing Cashew Nut Shell Ash (CNSA), Rice Husk Ash (RHA), Sugarcane Bagasse Ash, (SCBA), Palm Oil Fuel Ash (POFA) etc.

Table 2. Standards of Chemical Composition of Portland Cement.

Standard	**Chemical Compositions (%)**							
	CaO	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**SO_3**	**MgO**	**Na_2O**	**Loi**
GS 1118 [10]	64.18	21.02	5.04	2.85	2.58	1.67	0.24	11±1
BS EN 197-1 [11]	62.56	19.77	4.90	2.30	3.08	2.64		1.65

SANS 50197-1 [28]	65.00	20.70	4.60	2.60	2.90	1.70	0.10	2.90

Source: Authors' Construct

Table 3a shows a comparative analysis of ashes originated from agricultural waste materials through furnace burning process.

Table 3. a Furnace Burning: Comparative Analysis and Interpretation of Chemical Composition of Ashes from Agro-Waste Materials.

Researcher	**Material**	**Calcination Temperature**	**Composition of Oxides in Percentages (%)**							
			CaO	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**SO_3**	**MgO**	**Na_2O**	**Loi**
GS 1118 [10]	OPC	1450°C	64.18	21.02	5.04	2.85	2.58	1.67	0.24	11±1
BS EN 197-1 [68]	OPC	1450°C	62.56	19.77	4.90	2.30	3.08	2.64		1.65
SANS 50197-1 [28]	OPC	1450°C	65.00	20.70	4.60	2.60	2.90	1.70	0.10	2.90
Korankye and Danso [29]	Cashew Nut Shell Ash	735°C (32hrs)	6.34	38.36	42.14	0.01	0.12	4.26	0.33	11.46
Oyesibi et al. [3]	Cashew Nut Shell Ash	750°C (5hrs)	8.86	63.95	14.95	12.51	0.96	1.53	0.34	2.65
Sule and Ehikwe **[32]**	Cashew Nut Shell Ash	750°C (7hrs)	0.91	62.38	14.78	11.86	0.98	1.53	--	--
Tantri et al. [33]	Cashew Nut Shell Ash	750°C (8hs)	25.80	11.00	13.31	27.93	0.12	0.11	2.96	2.15
Tantri et al. [34]	Cashew Nut Shell Ash	750°C (8hs)	25.81	11.05	12.38	26.93	0.20	0.13	3.25	2.10
Odeyemi et al. [42]	Bamboo Leaf Ash	700°C	2.50	72.81	3.49	2.00	0.15	0.17	-	5.71
Ainomugisha et al. [43]	Sugarcane Bagasse Ash	700°C	1.59	68.43	9.04	10.84	1.02	0.88	-	-
Umar and Musa [44]	Corn Cob Ash	600-700°C	4.82	66.12	10.34	3.91	0.29	2.47	0.39	6.28
Umar and Musa [44]	Coconut Shell Ash	700-800°C	8.91	36.85	22.57	7.68	0.34	4.23	0.52	5.72
Adetoya et al. [61]	Cassava Peel Ash	--	10.20	51.79	9.57	4.23	1.52	2.90	1.37	6.10

Adetoya et al. [61]	Wood Ash	--	8.00	42.50	17.00	5.40	4.80	3.00	1.70	7.16
Alaneme [45]	Sugarcane Bagasse Ash	600 – 750°C	6.87	75.75	2.84	1.77	1.37	-	-	2.08
Alaneme [45]	Banna Peel Ash	600 – 750°C	7.32	14.06	6.04	3.74	1.84	-	-	4.11
Muhammed [69]	Rice Husk Ash	≤ 750°C	10.59	55.09	8.25	6.22	-	1.02	1.89	13.02
Hasan et al. [62]	Corn Cob Ash	500 – 600°C	11.99	67.03	7.82	4.25	1.12	1.99	0.42	1.63
Gunduz and Kalkan [46]	Rice Husk Ash	700°C	1.37	87.8	0.46	0.26	-	0.42	1.22	3.09
Pushpakumara and Mendis [47]	Rice Husk Ash	620°C	1.28	90.04	1.83	1.37	-	0.73	0.42	1.72
Sekunowo et al [35]	Cashew Nut Shell Ash	800°C (5hrs)	--	15.02	0.28	1.92	--	13.03	--	41.67
Oyesibi et al. [30]	Cashew Nut Shell Ash	(undisclosed)	2.04	65.02	16.28	10.16	1.32	1.53	0.45	2.95
Kareem et al. [36]	Cashew Nut Shell Ash	600°C (4hrs)	8.34	56.82	6.08	1.62	0.39	6.59		5.32
Tom and Joes [41]	Cashew Nut Shell Ash	Cashew Nut Shell Ash	620°C	7.50	47.50	3.00	3.00	-	1.90	-
Al-Hokabi et al. [54]	Palm Oil Fruit Ash	800 – 1000°C	13.2	35.90	1.33	8.71	1.39	1.24	-	-
Arel and Aydin [48]	Rice Husk Ash	600°C	1.30	88.40	0.21	1.10	0.40	0.20	0.40	2.80
Arel and Aydin [48]	Coconut Husk Ash	600°C	4.30	42.50	17.70	8.17	0.55	0.71	0.93	6.51
Olaiya et al. [63]	Sawdust Ash	600-800°C	9.87	66.95	5.12	2.26	1.36	5.92	-	4.37
Olaiya et al. [63]	Banana Leaf Ash	600-750°C	29.09	22.56	8.19	1.06	1.95	5.73	-	4.06
Ghazzawi et al. [49]	Olive Waste Ash	500°C	36.13	24.73	3.41	3.83	0.03	2.81	1.42	14.70
Singh et al. [50]	Wheat Husk Ash	600°C	5.46	43.22	-	0.84	-	0.99	0.16	-

Singh et al. [50]	Sugarcane Straw Ash	600^{o}C	12.20	70.24	1.93	2.09	-	1.95	-	-
Jamwal et al. [51]	Cow Dung Ash	800^{o}C	16.76	27.23	2.90	-	-	4.64	-	-
Jamwal et al. [51]	Corn Straw Ash	500^{o}C	14.53	10.31	-	-	-	4.39	-	-
Nagarajan et al. [52]	Coconut Shell Ash	600-800^{o}C	4.98	37.97	24.12	15.48	0.71	1.89	0.95	11.94
Sathiparan [53]	Egg Shell Ash	700^{o}C	74.60	0.04	0.01	0.01	-	0.25	0.13	-
Sathiparan [53]	Rice Shell Ash	650^{o}C	0.61	91.04	0.38	0.45	-	0.29	0.97	-

Source: Author's Construct

The comparative analysis in Table 3a depicts that the chemical compositions of agro-waste ashes manufactured through the method of controlled furnace burning constantly differ from industry cement standards. More especially, studies with calcination temperature below 600^{o}C produced low CaO. For example; Ghazzawi et al. [49] on Olive waste ash (CaO 36.13%) and Jamwal et al. [51] on corn straw ash recorded (CaO 14.53%) while majority of researchers who produced ashes above 700^{o}C reported deficiency of CaO since higher temperature degrades the CaO reducing its content in ashes. For instance, Korankye and Danso [29] on cashew apple ash (CaO = 6.34%), Sule and Ehikwe [32] on cashew nut shell ash (CaO = 0.91%), Alaneme [45] on bamboo peel ash (CaO = 7.32%) Al-Hokabi et al. [54] on palm oil fruit ash (CaO = 13.20%) etc. were all below standard requirement as supplementary cementitious materials (SCMs) due to low calcination temperature and poor processing of ashes. CaO is an oxide that reacts with silica to form calcium silicate hydrate to enable the material fulfil its hydration characteristics and strength development purposes, and therefore, its deficiency renders the material unsuitable for use as SCM [9].

Additionally, other oxides namely; SiO_2, Al_2O_3 and Fe_2O_3 play vital roles in SCMs. SiO_2 is the oxide that enhances the durability property of the material when formed with calcium silicate hydrate (C – S – H) in the hydration process imparting strength development while minimizing void ratio. Also, Al_2O_3 is responsible for controlling the setting time of the material and reacts quickly with calcium aluminate hydrate (C – A – H) in the hydration process that contributes early hardening of the material. Comparatively, some studies reported excess or low of these oxides for example, Korankye and Danso [29] on cashew apple ash (SiO_2= 8.36%, Al_2O_3 = 42.14%, Fe_2O_3 = 0.01%), Tantri et al. [33] on cashew nut shell ashes (SiO_2= 11.00%, Al_2O_3 = 13.31%, Fe_2O_3 = 27.93%), Gunduz and Kalkam [46] on rice husk ash (SiO_2= 87.80%, Al_2O_3 = 0.46%, Fe_2O_3 = 0.26%), Al-Hokabi et al. [54] on palm oil fruit ash (SiO_2= 35.90%, Al_2O_3 = 1.33%, Fe_2O_3 = 8.71%) and many others who reported excess or low of SiO_2, Al_2O_3 and Fe_2O_3 confirmin[5,7,13g that producing ashes from agro-waste materials above 700^{o}C ruins the formation of the chemical composition of the material making it inappropriate for use as SCM in the construction industry [5,7,13].

Unfortunately, the trend remains the same when some studies produced ashes in compliance with standard recommended calcination temperature yet recorded either low or high content. For example; Odeyemi et al. [42] on bamboo leaf ash (CaO = 2.50%, SiO_2= 72.81%, Al_2O_3 = 3.49%, Fe_2O_3 = 2.00%), Umar and Musa [44] on corn cob ash (CaO = 4.82%, SiO_2= 66.12%, Al_2O_3 = 10.34%, Fe_2O_3 = 3.91%), Tom and Joes [41] on cashew nut shell ash (CaO = 7.50%, SiO_2= 47.50%, Al_2O_3 = 3.00%, Fe_2O_3 = 3.00%) etc. Though the calcination temperature in these studies were within the recommended temperature, results were reported outside the standard recommended values. These differences and inconsistences in results could be attributed to prolong time which the material remained in the furnace before taking it out for further processing since, extreme calcination or calcination beyond 120 minutes negatively affects the oxide formation [5,7,13].

Table 3b indicates a summary of analysis of the chemical compositions of agro-waste materials manufactured using furnace burning method, condensing the degree of conformity with industry cement standards. It emphasizes the regular configuration of smaller CaO and larger SiO_2 and Al_2O_3 contents when calcination is over 700°C or calcination time exceeds 120 minutes.”

Table 3. b Calcination Temperature vs trends of Oxides in Agro-waste Materials.

Temperature	**CaO Trend**	**SiO_2 Trend**	**Al_2O_3 Trend**	**Fe_2O_3 Trend**	**Overall suitability as SCM**
< 600°C	Low	Low	Low	Low	Poor activation (unsuitable)
600 – 700°C	Acceptable	Acceptable	Acceptable	Acceptable	Time sensitive: needs time control (suitable)
> 700°C	Too low	Excess	Excess	Too large	Unsuitable

Source: Authors’ Construct

Generally, the proof from furnace burning deployed shows that calcination temperatures more than 700°C or excessive calcination time beyond 120 minutes constantly result in chemical disparities: low CaO and extremely large SiO_2 and Al_2O_3 levels. The maximum manufacturing window was reported to be 600–700°C for close to 90–120 minutes, as oxide stabilities are close to industry standards. Refusing to adopt this range negatively affect the reactivity of agro-waste ashes and makes them inappropriate as supplementary cementitious materials.

4.2. Open-Air Burning: Comparative Analysis and Interpretation

Table 3c indicates a comparative analysis of chemical composition of ashes produced from agro-waste materials through open-air burning method.

Table 4. Open-Air Burning: Comparative Analysis and Interpretation of Ashes from Agro-Waste Materials.

Researcher	**Material**	**Calcination**	**Composition of Oxides in Percentages (%)**							
		Temperature	**CaO**	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**SO_3**	**MgO**	**Na_2O**	**Loi**
GS 1118 [10]	OPC	1450°C	64.18	21.02	5.04	2.85	2.58	1.67	0.24	11±1
BS EN 197-1 [68]	OPC	1450°C	62.56	19.77	4.90	2.30	3.08	2.64		1.65
SANS 50197-1 [28]	OPC	1450°C	65.00	20.70	4.60	2.60	2.90	1.70	0.10	2.90
Manjunath et al. [37]	Cashew Nut Shell Ash	Open-Air	11.20	5.73	1.50	3.24	0.20	16.30	3.02	4.50
Mendu and Pannem [38]	Cashew Nut Shell Ash	Open-Air	21.50	37.67	5.80	2.00	0.80	5.32	3.11	14.16
Thirumumgan et al. [39]	Cashew Nut Shell Ash	Open-Air	35.58	54.85	2.01	4.20	0.80	1.85	--	0.71

Augias et al. [67]	Cashew Nut Shell Ash	Open-Air	16.72	5.66	2.30	5.34		6.88		
Pandi and Ganesan [40]	Cashew Nut Shell Ash	Open-Air	35.67	62.85	2.01	4.20	--	1.85	0.80	--
Kalasur et al. [64]	Pond Ash	Open-Air	0.73	4.17	4.36	8.27	-	-	-	-
Fernando et al. [55]	Groundnut Shell Ash	Open-Air	10.20	30.16	6.27	2.69	5.87	5.73	13.27	22.00
Ondego et al. [56]	Groundnut Shell Ash	Open-Air	19.61	18.14	7.07	5.86	1.23	5.98	-	-
Ondego et al. [56]	Groundnut Shell Ash	Open-Air	19.61	18.14	7.08	5.86	1.23	5.98	-	-
Oladele et al. [57]	Corn Cob Ash	Open-Air	32.30	41.10	4.90	3.60	0.98	2.10	2.40	-
Yaw et al. [66]	Cocoa Pod Husk Ash	Open-Air	0.00	9.73	3.44	0.45	2.17	4.30	-	-
Salim et al. [58]	Sugarcane Bagasse Ash	Open-Air	2.80	73.00	6.70	6.30	-	3.20	1.10	0.90
Sharma et al. [59]	Sugarcane Bagasse Ash	Open-Air	4.65	74.14	2.32	1.73	1.69	3.68	0.51	-
Bheel et al. [65]	Corn Cob Ash	Open-Air	10.75	67.23	6.34	5.33	1.04	-	0.37	-
Aboubacar and Alphonse [60]	Coconut Shell Ash	Open- Air	6.39	44.75	14.24	12.50	0.87	8.23	0.49	7.34

Source: Author's Construct

From Table 4, the results indicate that this method yields more unreliable oxide values, generally due to the uncontrolled temperatures and movable oxygen source coupled with open-air burning. CaO contents are acutely small among all reported studies, stretching from 0.91% to 11.15%, which were far lower than the industry standard of 50–65% [10,11]. This continual deficiency support that open-air burning does not maintain enough of chemical oxides of agro-waste ashes [5,6,13]. More so, SiO_2 and Al_2O_3 contents are excessively larger. Reported values for SiO_2 are always above 60%, whereas Al_2O_3 had been recorded up to 42.14%, larger than the recommended ranges of 20% and 4–5%, respectively. These outcomes propose extreme crystallization of silica and alumina levels, a general effect of longer duration and irregular and uncontrollable burning temperature. Fe_2O_3 contents also varied broadly, from as low as 0.01% to over 27%, mirroring the unpredictability of open-air burning. Such inconsistencies decrease the material's possibility for use in cement-based applications.

The open-air burning produces ash from agro-waste materials with lower chemical compositions as compared to the industry standards. Prior studies like Ondego et al. [56] and Fernando et al. [46] produced groundnut shell ash with large content of CaO but increased unrestrained oxide supplies showing the effect of uneven burning. Also, Oladele et al. [57] and

Aboubacar and Alphonse [60] who produced corn cob and coconut shell ash respectively reported a reasonable content of SiO_2. Producing ashes through open-air burning often results in wide variations of chemical compositions due to greater content of LOI which shows incomplete burning. This method hinders amorphous silica development while reducing the formation of Al_2O_3 and Fe_2O_3 to promote pozzolanic reactions. The results completely showed not only larger variations of chemical compositions but were also unreliable and non-conforming to industry standards.

In short, the results established that open-air burning is inappropriate for manufacturing pozzolanic-grade CNSA, as it constantly leads to deficient CaO and larger SiO_2 and Al_2O_3 contents. Compared to furnace-controlled calcination, open-air method does not provide consistent chemical compositions needed to meet industry cement standards. Hence, controlled furnace burning at 600–700°C for 90–120 minutes continues to be the recommended method for manufacturing CNSA that is chemically sustainable as a supplementary cementitious material [5,7,13].

4.3. Comparative Results of Physical Properties of Agro-Waste Ashes

Out of the 50 published articles selected for the study, a very few studies reported the physical properties of agro-waste ashes to show the various forms and their individual functions. Omoniyi and Okunola [16] discovered that the physical properties influence the quality of cementitious materials especially; fineness of the material, soundness, consistency, setting time, heat of hydration, Loss on ignition and specific gravity (relative density). Therefore, these physical properties of pozzolan cement impact positively on the structures' serviceability, strength, and durability necessitating the test for these properties [16]. Table 5 presents prior researchers' reports on the physical properties of agro-waste ashes through both furnace and open-air burning process.

Table 5. Comparative Analysis of Physical Properties of Agro-Waste Ashes through Furnace & Open-Air Burning.

Researcher	**Material**	**Temp (°C)**	**Specific gravity (%)**	**Fineness (m^2kg)**	**Initial setting (mins)**	**Final setting (mins)**	**Consistency (A ± 1)**	**Loi (%)**
BS EN 196-6 [619], BS EN 196-3 [22]	OPC	1450	3.15	320	60	600	10	3.00
BIS IS4031-P2 [23]	OPC		3.15	320	60	600	10	3.00
ASTM C204 [19], ASTM C1702-09 [21]	OPC		3.15	320	60	600	10	3.00

Oyebisi et al [3]	Cashew Nut Shell Ash	750	3.10	605				2.65
Kalasur et al. [64]	Pond Ash		2.63	2.95				
Umar and Musa [44]	Corn Cob Ash	700-800	4.10	876				
Ondego et al. [56]	Groundnut Shell Ash	Open-Air	1.57	443				
Oyebisi et al [30]	Cashew Nut Shell Ash	Open-Air	2.85	505				2.95
Pandi and Ganesan [40]	Cashew Nut Shell Ash	Open-Air	3.02		50	430	30	
Sathiparan [53] (2023)	Egg Shell Ash	700	1.25					
Sathiparan [53]	Rice Shell Ash	650	1.80					
Jamwal et al. [51]	Cow Dung Ash	800	2.80					
Jamwal et al. [51]	Corn Straw Ash	500	2.00					
Gunduz and Kalkan [46]	Rice Husk Ash	700	3.12		146	198		3.09
Al-Hokabi et al.[54]	Palm Oil Fruit Ash	800 – 1000^{o}C	2.25					

Source: Author's Construct

Neville [9] reported that calcining agro-waste ashes with temperature ranging from 600 – 700°C enhances the formation of the physical properties of the material required by industry standards ASTM C204 [19], BS EN 196-3 [20], ASTM C1702-09 [21], BS EN 196-6 [22], and BIS IS 4031-P2 [23] as compared with ordinary Portland cement manufactured at 1450°C. From Table 5, standards require specific gravity (3.15%), fineness (320m^2/Kg), setting times (60mins and 600mins) for initial and final setting respectively as well as LOi (3%). However, agro-waste ashes produced by prior researchers below the recommended calcination temperature (600 – 700°C) frequently recorded larger discrepancies. More so, there is no temperature control in open-air burning, which resulted in wide differences in the physical properties. For example, Oyebisi et al. [3] on CNSA at 750°C burning and Gunduz and Kalkan [46] on rice husk ash at 700°C reported specific gravity values close to standard limits indicating enhanced mineral densification through temperature control, although Oyebisi et al. [3] on CNSA at 750°C was outside the recommended calcination limit. Also, other furnace calcination produced ashes like corn cob ash with 4.10% and many others reported values largely outside the standards requirement that could result to potential mix proportioning challenges, segregation risks, and unpredictable strength development. additionally, prior reporters on groundnut shell ash like Ondego et al. [56] produced specific gravity (1.57%) which is lower than standard limits.

The results in Table 3 clearly show that agro-waste ashes manufactured particularly through furnace burning method recorded fineness values from 605–876 m^2/kg. As more fineness improve reactivity and filler effects, too much of fineness of the material is always as a result of excessive calcination temperature. Higher fineness of materials needs more water ratio during mixing which impact negatively the material's workability. On the other hand, open-air burning indicated large differences in fineness explaining the uncontrolled burning that led to incomplete combustion.

From Table 5, setting times and consistency of agro-waste ashes were reported within the standard requirements by few studies like Gunduz and Kalkan [46] and Pandi and Ganesan [40] and since, these were produced within the recommended ranges (600 – 700°C) suggesting the agreement of hydration. Unfortunately, refusal by most studies particularly the open-air manufacturing method to report data on setting times and consistency of agro-waste ashes hinders conclusion of outcome as this emphasis inconsistency of methodology.

Majority of studies reported values for LOi of agro-waste ashes produced through furnace burning method nearly satisfying industry standard requirements of 3% showing little or no organic matter in the ashes produced. Though, open-air burning in some studies recorded values of LOi within standard threshold, this method is more unreliable with high risk of unburnt carbon [6,7,13].

Generally, the results confirmed that producing agro-waste ashes within calcination temperature ranging from 600 – 700°C is the best calcination window for improving both the chemical and physical properties of agro-waste ashes [6,7,13] whereas open-air burning method often fails to retain reliable chemical oxide compositions and reproducible physical properties of the material. Also, only a few studies reported specific gravity results out of the many published articles. Therefore, this gab negatively affects comparative assessment that deepens the reason for producing agro-waste ashes and record physical properties which meet industry standards requirements.

5. Findings

The systematic review of 50 studies on agro-waste ashes revealed the following key findings:

1. That the chemical performance of agro-waste ashes is largely dependent on the calcination temperature and the time duration in which the material remains in the furnace before taking it out for further processing. Whereas the uncontrolled manufacturing of agro-waste ashes often results in wide differences in chemical compositions.

2. Ashes with CaO deficiencies (0.91 – 25.80%) was attributed to inconsistencies in both furnace and open-air burning methods, making the materials unsuitable for use as SCMs as required by GS 1118 [10], SANS 50197-1 [28], EN 197-1 [11], and standards.

3. Prior studies reports that larger content of SiO_2 and Al_2O_3 produced in ashes obtained through calcination temperatures above 700^oC or manufactured from open-air burning method result in imbalance of chemical composition, and thereby minimizing pozzolanic reliability.

4. Open-air burning method results in high value of LOi and irregular chemical composition of the ashes, confirming the method's inappropriateness for manufacturing standard agro-waste ashes for use as SCMs in the construction industry.

5. Appropriate or standard chemical compositions are obtained from control furnace burning method revealing that temperatures ranging from 600 – 700^oC and calcination times from 90 – 120 minutes, are the best manufacturing windows.

6. Literature review discovered that majority of researchers' attention is focused on reporting the chemical composition of agro-waste ashes with a few studies evaluating the physical properties, hindering standard-based assessment.

7. It is realised that agro-waste ashes produced through controlled furnace at calcination temperature between the recommended temperature (600 – 700^oC) improved on the physical properties like specific gravity, fineness, LOI which closely meet industry standard requirements.

6. Conclusions

Agro-waste ashes particularly cashew nut shell ash (CNSA), is potentially suitable for use as sustainable SCM. However, their efficacy is greatly dependent on calcination temperature and time duration.

The inconsistencies in oxide compositions reported by prior researchers were as a result of excessive calcination temperatures and longer time duration as well as open-air burning method employed.

Wide deficiencies in CaO and larger content in SiO_2 and Al_2O_3 essentially hinders the hydration and strength developing potential of many agro-waste ashes.

Open-air burning method is not appropriate for manufacturing pozzolanic-based ashes since this method is uncontrolled with regards to temperature, oxygen supply and time duration for burning.

Controlled furnace calcination method between 600 – 700^oC and 90 – 120 minutes is the most appropriate method that constantly produce chemical oxide values almost satisfying industry standard requirements suitable for use as SCMs.

Failure to report the physical properties of agro-waste ashes poses a critical gab in the current agro-waste ashes' studies.

Progressive reports on the physical properties of agro-waste ashes are key evidence confirming sustainable application of agro-waste ashes in construction.

7. Recommendations

Grounded on the above findings and conclusions, the following recommendations are made:

1. Future research and industry applications should adopt furnace calcination at 600–700°C for 90–120 minutes as the standard protocol for producing agro-waste ashes for use as SCMs.

2. Open-air burning for manufacturing agro-waste ashes should be avoided since, it provides unreliable and inconsistent chemical compositions for structural applications.

3. Future exploratory studies should focus more on engineering properties validations (mechanical, durability and physical) of ashes manufactured guided by the specified maximum calcination benchmarks.

4. Research should extend beyond Nigeria and India to other cashew-producing countries to improve global understanding of profit gains in the construction industry.

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5. Policy makers and industry experts should develop guidelines and standards for agro-waste ashes production, similar to other existing supplementary cementitious materials.

6. It is recommended that subsequent experimental studies in agro-waste ashes should validate the performance characteristics (chemical and physical) of these materials in concrete, blocks, and earth stabilization for construction purposes.

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