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Beema Bamboo As An Alternate Fuel For Clinker Production: Ash Chemistry And Burnability Assessment

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Abstract: The cement industry is continuously exploring sustainable alternative fuels to reduce fossil fuel consumption and greenhouse gas emissions while maintaining clinker quality. Although several biomass fuels have been investigated, limited studies have evaluated the influence of biomass ash on clinker burnability and clinker chemistry. In the present study, Beema bamboo was investigated as a potential alternative fuel and compared with conventional coal and petroleum coke to assess its suitability for clinker production.

The fuels were initially characterized through proximate analysis, followed by elemental characterization of the combustion ash using Inductively Coupled Plasma (ICP) analysis. Beema bamboo exhibited a significantly lower ash content (1.7%) than coal (13%) and comparable ash content to petroleum coke (1.1%), indicating reduced ash input into the clinkerization process. The ICP analysis showed that Beema bamboo ash was predominantly composed of SiO_2 (47.55%) and CaO (25.90%), suggesting its suitability for clinker formation. Based on the ash characteristics, clinker samples were prepared by incorporating the respective fuel ashes into a common kiln feed. The resulting clinkers were characterized using X-ray Fluorescence (XRF), and their burnability was evaluated through clinker moduli and Bogue phase calculations.

The clinker produced using Beema bamboo exhibited clinker quality comparable to conventional fuels, with LSF (93.51), SM (2.19), AM (1.11), and free CaO (1.20%), indicating satisfactory burnability. The calculated clinker mineral phases showed 51.27% C_3S, 22.74% C_2S, 5.80% C_3A, and 14.11% C_4AF, demonstrating clinker chemistry comparable to that obtained using coal and petroleum coke.

The findings indicate that the lower ash generation and favourable ash chemistry of Beema bamboo do not adversely affect clinker formation or burnability, highlighting its potential as a sustainable alternative fuel for clinker production in the cement industry.

Key Words: Alternative fuel, coal, pet coke, Beema bamboo, moisture content, volatile matter, fixed carbon, ash content, burnability, clinker

Introduction:

Cement production requires significant energy as kiln operations need very high range of temperatures ranging 1450-1500°C [1]. Roughly 20-25% of the production cost is attributed to thermal energy, predominantly used for raw material combustion [2]. At the COP 26 summit in Glasgow in November 2021, India had committed to cut CO_2 emissions and had set a Net Zero Carbon target by the year 2070 [3]. For the reduction of 1 billion tonnes of total projected CO_2 emissions by 2030, the cement sector has a significant contribution of 32 million tonnes of CO_2 reduction from energy conservation [4]. Carbon Footprint and switching to alternative resources of fuel are the two main methods for achieving this. Globally, cement producers have been exploring alternative fuel options since 1980s. Because of the high-ranging temperatures in the cement rotary kiln, diverse materials can be burnt in it. The alkaline environment within the kiln and clinker's ability to encapsulate and entrap contaminants like heavy metals, make it favorable for utilizing alternative fuels [5]. "Alternative fuels" encompass waste materials from various industries and non-fossil fuels. These include solid, liquid, and gaseous forms like fuels derived from tyres, sewage sludge, biomass residues and other industrial and commercial wastes [6]. Diverse type of wastes is used in cement kilns which mandates careful selection and monitoring of operational processes required for each specific waste type [7, 8]. Numerous studies have explored the feasibility of various alternative fuels in terms of their characteristics, emissions, and environmental impact to take the place of conventional fossil fuels in cement production [9].

Alternative fuels have different characteristics from conventional fuels which cause several challenges in shifting from conventional to alternative fuels. Some of the major difficulties faced are: lower distribution of heat, jamming in the preheater cyclones, unstable precalciner operation, aggregates in the kiln riser ducts, dusty kilns [10]. Traditional biomass often presents challenges due to variations in its calorific value and high moisture content, leading to inconsistent combustion and operational issues in cement production.
Dr. Barathi Nambi from India developed the plant Bambusa balcooa. It is a high-yielding species and is known for its rapid growth rate and thick culm walls. To enhance the biomass production and to make it one of the best biomass resources available, he cloned Beema bamboo. Beema bamboo has a calorific value of 4000 kcal/kg, low ash content (1.0%), and low moisture content. Thus it stands out due to its high energy content. It is a thornless, sterile variety that can sustainably grow without replanting for almost a hundred years. These unique properties make Beema bamboo applicable for carbon farming and it has attracted many industries, especially the cement industry to offset carbon footprints [11]. Biomass absorbs as much CO_2 during its growth as is released during its combustion, thus it is considered CO_2-neutral fuel [12]. NOx and SOx levels can be reduced by co-firing biomass fuels along with coal [13]. Bamboo is used in various industries like pulp and paper, food and feedstock, biofuel and energy, building and construction material, textile and composite, furniture, and medicine due to its versatile properties [14]. Pyrolysis is the technique which is most commonly used to produce charcoal, pellets, and preprocessing for producing ethanol and methanol from bamboo [15].
Bamboo charcoal is considered a high-quality fuel and is associated with low emissions during fuel combustion due to its high biomass density (300–900 kg/m3) [16]. In a study ash content, volatile matter content and fixed carbon content and calorific value of bamboo ranged between 9.66-1.91%, 73.1%-79.2% and 18.6%-23.4%, 4336-4909 kcal/kg [17]. In a research proximate analysis and calorific value of Bamboo leaves was studied where moisture percentage is found to be 7.7%, volatile matter is 68.7%, ash content is 12.3%, fixed carbon is 11.3% and Gross Calorific Value is 3756 kcal/kg [18]. The study explores the potential of utilizing bamboo waste materials such as bamboo stalks, sheaths, and leaves for the production of high-energy briquettes. The calorific values of bamboo stalks, sheaths, and leaves were determined to be 4660, 4100, and 3680 kcal/kg respectively, with volatile content ranging from 72.5% to 79% [19]. Bamboo fuel sources are sustainable, cleaner than traditional fuel sources as NOx and SOx generated during combustion create lower air pollution and the carbon released during its combustion, the same amount of carbon is stored by bamboo during its growth [20]. Bamboo charcoal has a high calorific value similar to

conventional wood (6965 kcal/kg, compared to 7785 kcal/kg for acacia charcoal). Bamboo charcoal burns clean (smokeless) because bamboo has relatively less volatile matter [21]. In cement manufacturing use of agricultural biomass as an alternate fuel is predominantly observed in agriculture-based developing countries like India, Thailand, and Malaysia. Various types of biomass, including rice husk, corn stover, hazelnut shells, coconut husks, coffee pods, and palm nut shells, are currently incinerated in cement kilns. However, the heating value of biomass varies between 3346 to 5019 kcal/kg, with 6% to 12% moisture content. Due to biomass's lower heating values in comparison to heavy fuel oil, modifications in burner design and adjustment to excess air is required. To produce high-density fuel from low-density biomass, high temperature and pressure is also necessary [22]. Both NO_X and SO_X levels can be reduced by co-firing biomass with coal [23].

The rapid growth rate and high yield of Bamboo make it suitable for various applications, including carbon farming to offset carbon footprints [24]. It is also suitable for paper production as a research studied that the six-month old fiber of Beema Bamboo and *Oxythenantera abyssinica* obtained 1.89 to 2.39 mm length 0.025-0.031 mm diameter [25]. Vegetative propagation/ macro propagation is simple, easy, and cost-effective, mass propagation of Bamboo can be done from offsets, layering, culm cuttings, and also through tissue culture [26].

Beema Bamboo is less dense, has high organic carbon and hydrogen content (9.95%), low oxygen (33.27%), nitrogen (0.69%) and sulphur content (0.59%). Its fixed carbon content (28.36%) indicates that it has good heating values.[45] The species has efficient combustion and low nitrogen and sulphur emissions. The ash contents (3.17%) and volatile matter recorded (60.84%) make it suitable raw material for solid biofuel production. The gross calorific value 5550 kcal/kg and net calorific value 5304 kcal/kg make it adaptable for high energy-requiring processes [27]. Bamboo can be a source of green energy in various forms like pellets, bio-ethanol, and charcoal. Bamboo charcoal has a high calorific value of 7887 kcal/kg when burned at 500-800 °C. Bamboo fuel sources (pellets, biogas, CH_4, *etc.*) are sustainable, cleaner than traditional fuel sources as NO_x and SO_x generated during combustion create lower air pollution and the carbon released during its combustion, the same amount of carbon is stored by Bamboo during its growth [28].

2. Materials and Methods:

2.1. Materials:

In this study, the raw material used were Beema bamboo stalk, Beema bamboo sheath, Beema bamboo leaves, coal, pet coke, raw materials for kiln feed (limestone, laterite, bauxite, red ochre) respectively.

2.2. *Sampling:*

The method used for sampling of agricultural waste and coal was based on ASTM D2234/D2234M to get a representative and significant sample. Sample’s minimum volume was taken according to particle size and bulk density followed by mixing and reduction by quartering coning, a minimum of 5-10 kg of sample was collected for testing. Sampling of pet coke was done by standard ASTM D6970.

2.3. *Sample preparation:*

The sample received in the laboratory was first weighed and the weight was recorded. The sample was then spread on a wide non-corrodible tray. The non-malleable contaminants (metal pieces, rock and glass pieces, if any) were separated from the sample by magnetic and manual sorting. The separated portions was weighted again and the weights were recorded. The whole sample was then sieved to separate the fines (dust, clay etc.). The millable sample was then fed to the Fritsch Pulverisette cutting mill. The sample was further crushed in the cutting mill to a fine powder passing through a 500-micron sieve and collected in a container attached just below the crushing unit. The sample was then preserved in sealed containers or pouches for test determinations.

2.4. *Proximate Analysis:*

Thermo Gravimetric Analyzer (TGA) from Leco, based on ASTM-5142 was used for determining the proximate analysis of all fuel, namely Beema bamboo, coal, per coke, sample taken for testing was 0.5mm sieve passed and equilibrated at 40℃. The TGA measured the change in weights with increase in temperature, in a controlled environment of air, enriched N_2 or O_2. Then a curve was plotted between temperature and change in weight.

2.4.1. *Moisture:*

Standard ASTM D 3173-87 was used to determine total moisture (TM) and inherent moisture (IM) content in a sample. 1-2 g of sample was taken in a crucible and placed in oven at 105°C-110°C until constant weight was achieved. Then the sample was removed and kept in desiccator to attain room temperature. The crucible was then weighed on analytical weighing balance and results were noted.

2.4.2. *Volatile matter:*

Standard ASTM D 3175-89 was used to determine volatile matter (VM) content in a sample.1-2 g of sample was taken in a covered crucible and placed in furnace at 950℃ for 7 minutes. Then sample was removed and kept in desiccator to attain room temperature. The crucible was then weighed on analytical weighing balance and results were noted.

2.4.3. *Ash:*

Standard ASTM D 3174-89 was used to determine ash content in a sample. 1-2g of sample was taken in a crucible and placed in furnace at 700°C-750°C until complete combustion. Then the sample was removed and kept in desiccator to attain room temperature. The crucible was then weighed on analytical weighing balance and results were noted.

2.4.4. *Fixed carbon:*

Fixed carbon (FC) was calculated after subtracting from 100 the sum of moisture, ash and volatile matter contents expressed as percent.

$$FC\ (\%) = 100 - (\text{Total Moisture} + \text{Volatile Matter} + \text{Ash})$$

2.5. Determination of Composition of Fuel Ash:

Induced couple plasma optical emission spectroscopy (ICP-OES) was used for determination of major elements (SiO_2, Fe_2O_3, Al_2O_3, CaO, MgO, SO_3 etc.), minor elements (Na_2O, K_2O, Mn_2O_3, TiO_2, P_2O_5. Mn_2O_3, Cr_2O_3 and Cl etc.). The ash samples (Beema bamboo, coal, pet coke) were ground into fine powder and approximately 0.1g-0.2g of each ash sample was digested using microwave-assisted acid digestion, using strong acids (nitric and hydrochloric etc.) at 180°C, 150 psi pressure for 1 hour. The dissolved samples were diluted with pure water, filtered, and analyzed using ICP-OES. The instrument was calibrated using certified reference materials matching fuel ash composition. Key elements like potassium, sodium, calcium, and heavy metals were measured at their specific detection wavelengths.

2.6. Clinker Preparation, Burnability Assessment & Characterization:

A common kiln feed was designed by maintaining the desired clinker moduli, namely Lime Saturation Factor (LSF), Silica Modulus (SM), and Alumina Modulus (AM). The respective fuel ash obtained from Beema bamboo, coal, and petroleum coke was incorporated into the kiln feed to prepare three separate clinker batches. The prepared mixes were pelletized and burned in a laboratory furnace at 1450°C with a soaking time of 30 minutes, followed by air cooling to room temperature. The burnability of the clinker samples was assessed by determining the free lime (f-CaO) content and evaluating the clinker moduli. The mineralogical composition of the clinker was estimated using the Bogue equations, and the liquid phase content was calculated to assess clinker formation and burnability.

2.7. Clinker Chemical Characterization:

The chemical composition of the clinker samples was determined using X-ray Fluorescence (XRF) analysis with an ARL 8000 XRF spectrometer. Pressed pellets were prepared from finely ground clinker powder and analyzed to quantify the major oxide composition, including SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, SO_3, Na_2O, K_2O, and Cl. The XRF results were used to calculate the clinker quality parameters, including Lime Saturation Factor (LSF), Silica Modulus (SM), Alumina Modulus (AM), and the theoretical Bogue phase composition (C_3S, C_2S, C_3A, and C_4AF). These parameters were compared among the clinker samples produced using Beema bamboo, coal, and petroleum coke to evaluate the influence of fuel ash on clinker chemistry and burnability.

3. Result and discussion:

3.1. Proximate Analysis:

Table 1 depicts the proximate analysis from which it can be concluded that Beema bamboo exhibits favorable properties, such as moderate moisture content, high volatile matter, and low ash content, making it suitable for combustion. The proximate analysis of Beema bamboo compared to coal and pet coke reveals its viability as an alternative cement kiln fuel. With 24.2% total moisture, Beema bamboo requires pre-drying to below 15% moisture for optimal combustion which can be done by using industrial dryers. Its exceptionally high volatile matter (77.4%) enables rapid ignition at lower temperatures (320-400°C), making it particularly suitable for precalciner zones where fast-burning fuels are advantageous. However, this characteristic demands modified combustion systems with staged air supply (primary: secondary = 30:70) to prevent incomplete combustion and CO formation. The remarkably low ash content (1.7%) presents multiple benefits: it reduces clinker contamination risks. While the fixed carbon content (16.4%) is substantially lower than fossil fuels (coal:65.1%, petcoke:85.6%), this actually benefits kiln operation by reducing the risk of unburnt carbon in clinker. The fuel's high volatile-to-fixed-carbon ratio (4.7:1) suggests optimal performance when used in precalciners (70-80% of thermal input) while maintaining a smaller fossil fuel fraction (20-30%) in the main kiln burner for temperature stability. When compared to other biomass options like rice husk (15-20% ash) or bagasse (8-12% ash), Beema bamboo's ultra-low ash content and consistent composition (due to sterile cloned propagation) give it distinct advantages for cement applications. The moisture content, while higher than fossil fuels, is actually lower than many agricultural residues (e.g., bagasse at 45-55%), reducing the energy penalty for drying. These properties collectively position Beema bamboo as a technically superior biomass alternative, particularly when implemented in a co-firing system that leverages its high volatility in precalciners while using conventional fuels or bamboo-derived char in the high-temperature sintering zone. The key operational modifications needed - primarily drying systems and combustion controls - are justified by the significant environmental benefits and long-term cost savings from reduced carbon liabilities.

Table 1. Proximate analysis of coal, pet coke & Beema bamboo

Fuel	TM%	IM%	VM%	ASH%	FC%
Coal	5.5	1.1	20.8	13	65.1
Pet coke	3.4	0.5	12.8	1.1	85.6
Beema bamboo	24.2	4.5	77.4	1.7	16.7

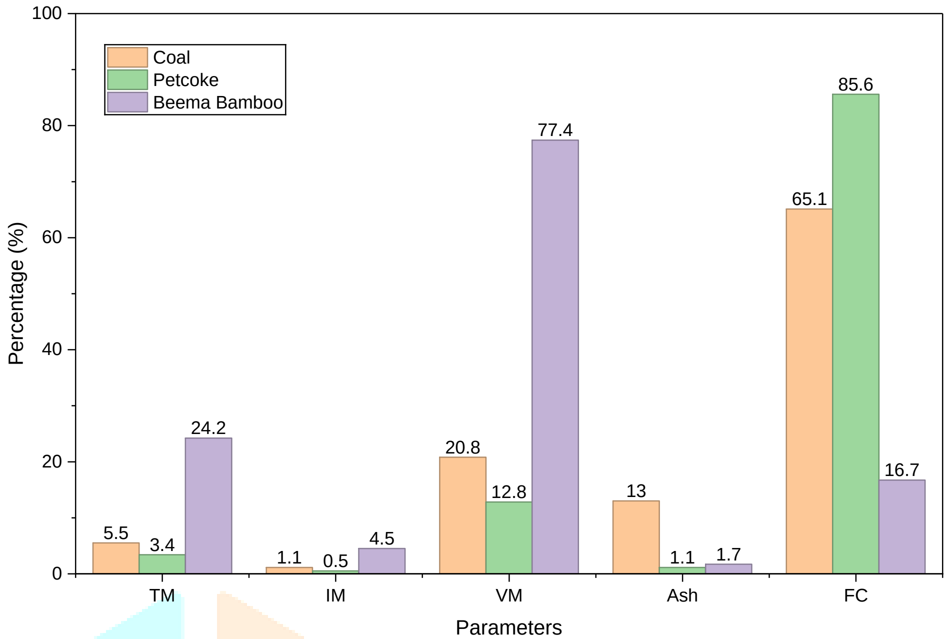

Fig. 1 Graph comparing proximate analysis of coal, pet coke & Beema bamboo

3.2. Fuel Ash Characterization by ICP–OES:

The chemical composition of the combustion ash obtained from Beema bamboo, coal, and petroleum coke is presented in Table 2. The results indicate significant variations in the oxide composition of the three fuel ashes, reflecting their distinct mineralogical characteristics and potential influence on clinker formation.

Beema bamboo ash was predominantly composed of SiO_2 (47.55%) and CaO (25.90%), whereas coal ash contained comparatively higher concentrations of Al_2O_3 (22.0%) and Fe_2O_3 (20.0%). Petroleum coke ash exhibited relatively lower CaO (6.50%) but the highest SO_3 content (5.23%) among the three fuels. The elevated silica and calcium oxide contents in Beema bamboo ash indicate that it can contribute beneficially to clinker formation by supplying major clinker-forming oxides. In contrast, the higher alumina and iron oxide contents of coal ash are expected to promote liquid phase formation during clinkerization, while the comparatively high sulphur content in petroleum coke ash may increase sulphur circulation within the kiln system.

The alkali content also varied considerably among the fuels. Beema bamboo ash exhibited the highest K_2O concentration (5.86%), while Na_2O contents were comparable for all three fuels. Higher alkali levels may influence kiln operation and clinker chemistry; however, their effect depends on the overall alkali input from the complete raw mix and kiln operating conditions. The concentrations of minor oxides, including TiO_2, Mn_2O_3, Cr_2O_3, BaO, ZnO, CuO, and SrO, were relatively low in all samples and are therefore expected to have only a limited influence on clinker mineral formation.

When considered together with the proximate analysis, Beema bamboo demonstrates favourable characteristics as an alternative fuel. Although its ash content (1.7%) is slightly higher than that of petroleum coke (1.1%), it is substantially lower than that of coal (13.0%), thereby reducing the quantity of mineral residue introduced into the clinkerization process. Furthermore, the predominance of silica and calcium oxide in Beema bamboo ash suggests compatibility with cement raw materials and supports its suitability for clinker production. Overall, the ICP–OES results indicate that the ash generated from Beema bamboo possesses a chemical composition suitable for use in cement kilns without adversely affecting the major clinker-forming oxides.

Table 2. Ash Analysis of Beema bamboo, pet coke & coal

Parameter	Beema Bamboo	Pet coke	Coal
SiO_2	47.55	44.50	40.60
Al_2O_3	4.28	25.50	22.00
Fe_2O_3	3.39	10.00	20.00
CaO	25.90	6.50	12.00
MgO	5.49	1.50	1.00
SO_3	1.34	5.23	3.12
K_2O	5.86	1.48	0.20
Na_2O	1.13	1.25	0.90
TiO_2	0.51	0.42	0.33
Mn_2O_3	0.35	0.33	0.27
P_2O_5	2.60	1.00	1.45
Cr_2O_3	0.01	0.03	0.01
BaO	0.10	0.10	0.08
ZnO	0.10	0.15	0.06
CuO	0.03	0.09	0.07
SrO	0.14	0.17	0.12
Cl	0.20	0.03	0.02

3.3. Clinker Chemistry and Burnability Assessment:

The chemical composition and burnability parameters of the clinker produced using Beema bamboo, coal, and petroleum coke are presented in Table 3. The results indicate that the incorporation of fuel ash from Beema bamboo into the kiln feed did not significantly alter the clinker chemistry, and the produced clinker exhibited characteristics comparable to those obtained using conventional fossil fuels.

Prior to clinkerization, the kiln feed was proportioned to achieve the target clinker moduli, and the corresponding quantity of fuel ash generated during combustion was incorporated into the ignited raw mix. The calculated ash contribution was 0.32% for Beema bamboo, 0.09% for petroleum coke, and 1.37% for coal, resulting in ignited mix proportions of 99.68%, 99.91%, and 98.63%, respectively. These values reflect the different ash yields of the fuels and demonstrate that the lower ash generation from Beema bamboo required only a marginal adjustment to the kiln feed composition compared with conventional fuels.

The XRF analysis showed that the major clinker-forming oxides remained within the desired range for all clinker samples. The clinker produced using Beema bamboo contained 21.42% SiO_2, 5.15% Al_2O_3, 4.64% Fe_2O_3, and 64.59% CaO, which were comparable to those obtained with petroleum coke and U.S. coal. The minor variations in oxide composition among the three clinkers indicate that the different fuel ashes had a negligible influence on the overall clinker chemistry.

The burnability of the clinker was evaluated using the clinker moduli, namely Lime Saturation Factor (LSF), Silica Modulus (SM), Alumina Modulus (AM), free lime (f-CaO), and liquid phase content. The Beema bamboo clinker exhibited an LSF of 93.51, SM of 2.19, and AM of 1.11, which closely matched the corresponding values for petroleum coke (93.82, 2.18, and 1.11) and coal (91.45, 2.11, and 1.11). The free CaO content remained constant at 1.20% for all clinker samples, indicating comparable clinkerization under identical burning conditions. Similarly, the liquid phase content varied only marginally, ranging from 27.95% to 29.09%, suggesting that the incorporation of Beema bamboo ash did not adversely affect the burnability of the kiln feed.

The theoretical clinker mineral composition, calculated using the Bogue equations, further confirmed the suitability of Beema bamboo as an alternative fuel. The Beema bamboo clinker contained 51.27% C_3S, 22.74% C_2S, 5.80% C_3A, and 14.11% C_4AF, which were comparable to the clinker mineralogy obtained using petroleum coke and coal. The balanced distribution of the principal clinker phases indicates that the incorporation of Beema bamboo ash did not significantly influence clinker formation under the adopted burning conditions.

Overall, the clinker chemistry and burnability results demonstrate that the lower ash generation and favourable ash composition of Beema bamboo are compatible with clinker production, yielding clinker characteristics comparable to those produced using conventional fossil fuels. These findings support the technical feasibility of Beema bamboo as a sustainable alternative fuel for cement manufacturing without compromising clinker quality or burnability.

Table 3. Clinker analysis for Beema bamboo, pet coke & coal against given kiln feed

Parameter	Kiln Feed	Beema Bamboo	Petcoke	Coal
SiO_2	14.02	21.42	21.63	21.74
Al_2O_3	3.38	5.15	5.23	5.41
Fe_2O_3	3.08	4.64	4.70	4.88
CaO	42.51	64.59	65.50	64.41
MgO	0.8	1.24	1.24	1.23
LOI	35.15	0.39	0.40	0.40
Na_2O	0.1	0.16	0.16	0.17
K_2O	0.35	0.55	0.54	0.54
SO_3	0.15	1.64	0.98	1.01
Cl	0.01	0.016	0.015	0.020
LSF	94	93.51	93.82	91.45
SM	2.18	2.19	2.18	2.11
AM	1.11	1.11	1.11	1.11
C3S (%)	-	51.27	54.16	47.77
C2S (%)	-	22.74	20.79	26.29
C3A (%)	-	5.8	5.88	6.09
C4AF (%)	-	14.11	14.23	14.85
F.CaO (%)	-	1.2	1.20	1.20
Liquid Content (%)	-	27.95	28.00	29.09

4. Conclusion:

This study evaluated the suitability of Beema bamboo as an alternative fuel for clinker production by comparing its fuel characteristics, ash chemistry, and clinker performance with those of conventional U.S. coal and petroleum coke. The proximate analysis revealed that Beema bamboo possessed a significantly lower ash content (1.7%) than coal (13%), indicating a reduced mineral residue entering the clinkerization process, while maintaining an ash content comparable to petroleum coke (1.1%).

The ICP–OES analysis demonstrated that Beema bamboo ash contained appreciable amounts of silica (SiO_2) and calcium oxide (CaO), the principal oxides required for clinker formation. The chemical composition of the ash indicated its compatibility with cement raw materials and suggested that its incorporation into the kiln feed would not adversely affect clinker chemistry.

The clinker produced using Beema bamboo exhibited chemical composition and burnability characteristics comparable to those obtained using conventional fossil fuels. The clinker moduli (LSF, SM, and AM), free lime content, and liquid phase remained within acceptable ranges, indicating satisfactory clinkerization under identical laboratory burning conditions. Furthermore, the theoretical Bogue phase composition confirmed that the principal clinker minerals formed in proportions comparable to those produced using coal and petroleum coke, demonstrating that the incorporation of Beema bamboo ash did not significantly influence clinker formation.

Overall, the results demonstrate that Beema bamboo can be considered a technically feasible alternative fuel for clinker production. Its favourable fuel characteristics, lower ash generation compared with coal, suitable ash chemistry, and comparable clinker quality indicate that it can be utilized without adversely affecting clinker burnability or chemical composition. The findings contribute to the growing body of research on biomass-based alternative fuels and support the potential application of Beema bamboo in promoting more sustainable and lower-carbon cement manufacturing.

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