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Beema Bamboo vs. Agricultural Wastes: A Comparative Proximate- Ultimate Analysis for Sustainable Fuel Application in Cement Kilns

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Abstract: Cement production requires significant energy as kiln operations need very high range of temperatures ranging 1450-1500°C. Coal and petroleum coke (petcoke) are the conventional fuels on which the Indian cement industry is primarily dependent, with an estimated annual consumption of 50 million tonnes of coal equivalent. Globally, 7% of total CO_2 is emitted by cement industries. Cement producers have been exploring alternative fuel options since 1980s. "Alternative fuels" encompass waste materials from various industries and non-fossil fuels. Despite extensive exploration of biomass and fossil fuel alternatives, Beema bamboo remains an untapped resource with its uniform composition and favorable properties. Beema bamboo is an innovative plant produced by tissue-culture, a modified and improved version of Bambusa balcooa. This study comprehensively evaluates Beema bamboo as a sustainable alternative fuel for cement manufacturing through comparative proximate, ultimate, calorific, and ash composition analyses with conventional agricultural wastes (rice husk, saw dust, mixed agricultural waste including soya husk, sarso husk, ground nut husk, wheat husk). Results demonstrate Beema bamboo's superior combustion properties, including high volatile matter (77.4%), ultra-low ash (1.7%), and optimal fixed carbon (16.4%), enabling efficient energy release while minimizing clinker contamination. Its environmental advantages are pronounced, with significantly lower sulfur (0.28%) and nitrogen (0.99%) content than mixed waste (0.56% S, 2.5% N), reducing SO_x/NO_x emissions. Despite a moderate gross calorific value (4,145 kcal/kg), its net calorific value (3,644 kcal/kg) surpasses rice husk and mixed waste, with further potential through moisture control (<15%). Critically, Beema bamboo's ash composition (25.9% CaO, 47.55% SiO_2, 5.86% K_2O) proves cementitious, capable of replacing 5–8% of limestone in raw mixes, unlike silica-dominated rice husk ash (89.3% SiO_2) or alkali-rich mixed waste (20.7% K_2O). A 70:30 blend with saw dust balances energy density (3,700 kcal/kg NCV) and emission reductions. With trace metals (Cr_2O_3: 0.01%) well below hazardous thresholds and carbon-negative lifecycle, Beema bamboo emerges as the most viable biomass fuel for decarbonizing cement production, requiring only modest kiln modifications for large-scale adoption.

Key Words: Alternative fuel, Beema bamboo, cement kilns, proximate analysis, ultimate analysis, calorific value, ash composition, biomass co-firing, decarbonization

1. Introduction:

Globally, 7% of total CO_2 is emitted by cement industries. Cement sector in India contributes to 4.2% of energy-related and 2.1% of process-related greenhouse gas emissions, which corresponded to 2531.1 million tonnes of CO_2 equivalent in 2016 [1]. At the Conference of the Parties 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 [2]. 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 [3]. Carbon footprint and switching to alternative resources of fuel are the two main methods for achieving this. The 2012 roadmap of Indian cement industry for Low Carbon Technology which was developed by the International Energy Agency and Cement Sustainability Initiative, highlighted alternatives to be used for fuel adoption as a key strategy to reduce carbon footprint, in association with the Confederation of Indian Industry and the National Council for Cement and Building Materials [4]. Globally, cement producers have been exploring alternative fuel options since 1980s. Because of the high-ranging temperatures and extended residence time of material in the cement rotary, kiln's 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]. Various types of agricultural biomass are employed, including rice husk, soya husk, saw dust, eucalyptus bark, subabul bark, plywood waste, coconut shell, ground nutshell, mustard husk, sugarcane trash, and soybean. Agricultural biomass is not commonly used globally as an alternative fuel in the cement industry. Type of biomass used varies too, widely depending on the crops grown locally [7] Biomass absorbs as much CO_2 during its growth as is released during its combustion, thus it is considered CO_2-neutral fuel. NOx and SOx levels can be reduced by co-firing biomass fuels along with coal [8]. Experimental data shows that using biomass results in lower SO_2 emissions, lower dioxin and furan emissions, and very low heavy metal emissions [9]. However, the unavailability of biomass throughout the year poses a major challenge. High variations in calorific value and high moisture content also pose challenges in using substantial amounts of agricultural biomass as fuel [10]. In cement manufacturing use of agricultural biomass as an alternate fuel is predominantly observed in agriculture-based developing countries like India, Thailand, and Malaysia. However, the heating value of biomass varies between 3346 to 5019 kcal/kg, with 6% to 12% moisture content [11]. Firing biomass along with coal helps to prevent the formation of alkaline and chlorine compounds in kiln, reducing concerns about chlorine content in certain biomass types like wheat straw and rice husks [12].

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 [13]. Bamboo is an important non-wood forest product; it grows very fast. The largest producer of Bamboo in Asia is India. It is known for its increased average yield, attracting industrial interest and investment in its cultivation. The rapid growth rate and high yield of Bamboo make it suitable for various applications, including carbon farming to offset carbon footprints [14].

The chemical composition of Beema Bamboo includes a high calorific value (4000 kcal/kg), low ash content (1%), and a biomass yield of 100 tons/hectare in a year. Beema Bamboo, due to its efficient properties is considered to be one of the most efficient biomass resources. As Beema Bamboo grows very fast, has no thorns and gives very high yield, it can be harvested in a sustainable manner almost annually [15]. 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 [16]. 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%. By blending Bamboo waste with sawdust, various compositions were tested to ascertain the optimal blend. It was found that a 50:50 ratio of Bamboo waste to sawdust resulted in briquettes of superior quality, exhibiting a bulk density of 705 kg/m³ and a calorific value of 4372 kcal/kg [17]. 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. 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 [18].

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 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 [19]. Bamboo charcoal has a high calorific value (6963 kcal/kg) like wood, compared to acacia charcoal (7785 kcal/kg). It burns smokeless because it contains negligible volatile matter [20]. Fuel briquettes produced from the homogenous combinations containing 100% (Bamboo char, maize cob char and charcoal dust), the test results range (8%-11%) moisture, (12%-23%) volatile matter, (33%-39%) ash, (3824-5258 kcal/kg) heating value, (30%-51%) fixed carbon [21].

2. Materials and Methods:

2.1. Materials:

In this study, the raw material used are Beema bamboo (stalk, sheath, leaves), rice husk, saw dust, mixed agricultural waste (soya husk, sarso husk, ground nut husk, wheat husk) respectively.

2.2. Sampling:

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

2.3. Sample preparation:

The sample received in the laboratory is first weighed and the weight is recorded. The sample is then spread on a wide non-corrodible tray. The non-malleable contaminants (metal pieces, rock and glass pieces, if any) are separated from the sample by magnetic and manual sorting. The separated portions are weighted again and the weights are recorded. The whole sample is then sieved to separate the fines (dust, clay etc.). The millable sample is then fed to the Fritsch Pulverisette cutting mill. The sample is 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 is then preserved in sealed containers or pouches for test determinations.

2.4. Proximate Analysis:

Thermo Gravimetric Analyzer or proximate analyser from Leco, based on ASTM-5142 is used for determining the proximate analysis of any fuel, sample taken should be 0.5mm sieve passed and equilibrated at 40℃. It measures the change in weights with increase in temperature, in a controlled environment of air, enriched N_2 or O_2. Then a curve is plotted between temperature and change in weight. Proximate analysis of any sample can be done using proximate analyser.

2.4.1. Moisture:

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

2.4.2. Volatile matter:

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

2.4.3. Ash:

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

2.4.4. Fixed carbon:

Fixed carbon (FC) is 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. Ultimate Analysis:

2.5.1. CHNS Analysis:

Alternate fuel samples should be 0.5mm passed or lower. For elemental analysis, the sample should be dry (dried at 107°C till no weight loss is there). The elemental analyzer, is used for C, H, N and S analysis. C, H, N are determined by using CHN-Analyser. C and H is determined through infra-red cell whereas nitrogen is determined through thermal conductivity cell. Gas required for analysis is pure oxygen and helium and also compressor for compressed air. Total sulphur is analyzed by using the S-Analyzer. For sulphur analysis sample is weighed in ceramic boats and inserted in a horizontally placed tubular furnace of the S-analyzer. Fuel when combusted completely in presence of dry air and pure oxygen, sulphur is converted to sulphur dioxide (SO2). Sulphur is detected and analyzed through infra-red detector.

2.5.2. Calorific Value Determination:

Gross calorific value (GCV) is determined using Automatic Bomb Calorimeter. It is a Digital Signal Processing (DSP) microprocessor-based instrument. The calorific value of a sample is done in a controlled environment. Sample is burnt in a controlled way in an aerobic environment and the heat released during combustion is equivalent to the calorific value of the substance. The determinations provide gross calorific value. The net calorific value is determined from gross calorific value.

$$\text{NCV (as received)} = \text{GCV (as received)} - (9 \times H + M/100) \times L$$

Where:

- GCV: Gross Calorific Value (kcal/kg).
- H: Hydrogen content of the fuel (% by weight, on a dry basis).
- M: Moisture content of the fuel (% by weight, on an as-received basis).
- L: Latent heat of vaporization of water (587 kcal/kg).
- 9: Conversion factor for hydrogen to water (1 kg of hydrogen produces 9 kg of water).

1.6 . Determination of Composition of Fuel Ash:

Induced couple plasma optical emission spectroscopy (ICP-OES) is 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 (from Beema bamboo, agricultural waste) are ground into fine powder and approximately 0.1g-0.2g of each ash sample is 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 are diluted with pure water, filtered, and analyzed using ICP-OES. The instrument is calibrated using certified reference materials matching fuel ash composition. Key elements like potassium, sodium, calcium, and heavy metals are measured at their specific detection wavelengths. This method precisely quantifies ash components that affect cement quality and kiln operations.

3. Result and Discussion:

Proximate analysis, ultimate analysis and ash analysis of Beema bamboo, saw dust, rice husk and mixed agricultural waste (soya husk, sarso husk, ground nut husk, wheat husk) was conducted.

3.1. Proximate Analysis:

Table 1 depicts the proximate analysis for these wastes as fuel. The proximate analysis reveals Beema bamboo's superior fuel characteristics compared to agricultural residues. While its total moisture (24.2%) is higher than rice husk (8.7%) and mixed agricultural waste (8.3%), this is offset by its exceptionally low ash content (1.7%) - 10× lower than rice husk (18.4%) and 13× lower than mixed waste (22%). This minimal ash reduces clinker contamination risks and kiln maintenance requirements, critical for cement production. Beema bamboo's high volatile matter (77.4%) enables rapid ignition, outperforming other biofuels (rice husk: 63.5%, saw dust: 73.8%), though requiring optimized combustion staging to prevent incomplete burning. The fixed carbon content (16.4%) is comparable across all fuels, but Beema bamboo's balanced VM/FC ratio (4.7:1) ensures more stable combustion than mixed waste (3.4:1). Beema bamboo's combination of moderate moisture (manageable via industrial dryers), ultra-low ash, and high volatility positions it as the most viable biomass alternative, particularly when blended with 20-30% high-FC fuels for sintering zone requirements.

Table 1 Proximate analysis of various alternate fuels

Parameter	Beema Bamboo	Rice Husk	Saw Dust	Mixed Agricultural waste
Total Moisture (%)	24.2	8.7	40.1	8.3
IM (%)	4.5	1.1	3	2.4
VM (%)	77.4	63.5	73.8	58.2
Ash (%)	1.7	18.4	5.5	22
FC (%)	16.4	17	17.7	17.4

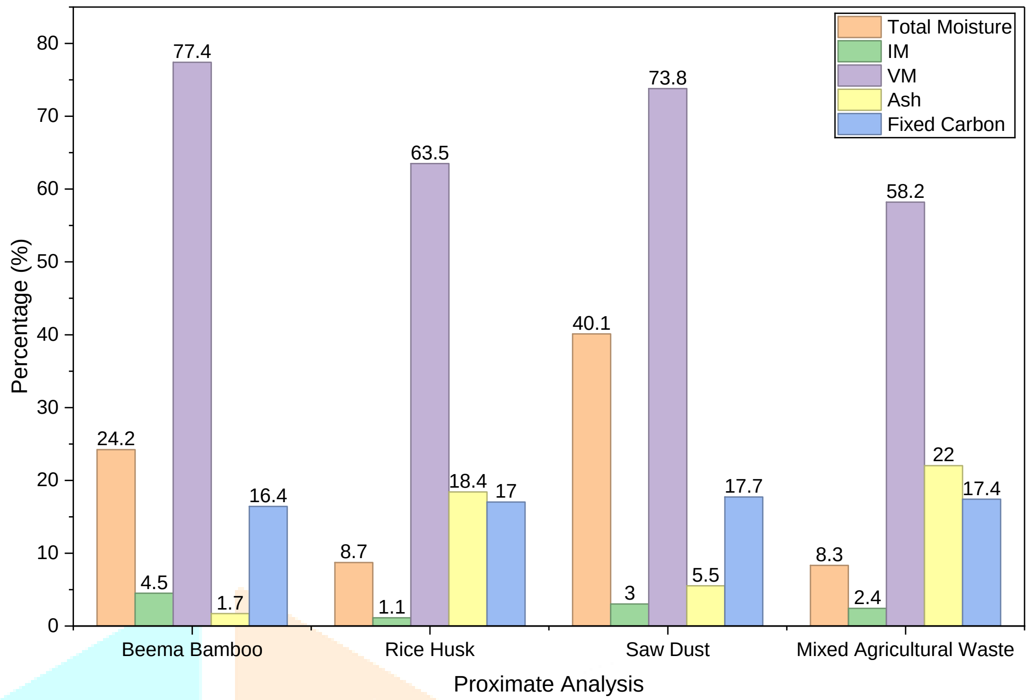

Fig 1. Graph comparing proximate analysis

3.2. C, H, N, S Analysis:

Table 2 discusses the carbon, hydrogen, nitrogen and sulphur percentage of the various alternative fuels. From the table it can be concluded that:

3.2.1. Sulphur Content Analysis

Beema bamboo exhibits a sulfur content of 0.28%, which is marginally higher than rice husk (0.1%) and saw dust (0.12%) but significantly lower than mixed agricultural waste (0.56%). While all tested biomass fuels fall well below the typical sulfur threshold for cement kilns (<1% as per ASTM D4239), the mixed agricultural waste's elevated sulfur level could contribute to minor SO_x emissions during combustion. Notably, Beema bamboo's sulfur content remains 85% lower than that of coal (typically 2-4%), making it an environmentally preferable option. The minimal sulfur presence in Beema bamboo eliminates the need for additional flue gas desulfurization systems, reducing operational costs in cement plants.

3.2.2. Carbon Content and Energy Implications

The carbon content analysis reveals striking differences among the fuels. Beema bamboo shows an exceptionally low carbon percentage (0.73%) compared to rice husk (29.7%), saw dust (43%), and mixed agricultural waste (41.2%). This aligns with its high volatile matter content (77.4% from proximate analysis), confirming its rapid combustion characteristics. While this low carbon content reduces its energy density, it also results in lower CO_2 emissions per unit of fuel burned. For practical kiln applications, blending Beema bamboo with high-carbon fuels like saw dust (43% C) could optimize both combustion stability and emission profiles.

3.2.3. Hydrogen Content and Combustion Behavior

With 6.8% hydrogen content, Beema bamboo surpasses other tested fuels (rice husk: 5%, saw dust: 5.6%, mixed waste: 4.3%). This elevated hydrogen concentration contributes to higher moisture retention in the fuel (consistent with its 24.2% total moisture content) and increased water vapor production during combustion. The latter effect can help mitigate NO_x formation through thermal quenching. This property makes Beema bamboo particularly suitable for precalciner zones where controlled combustion is critical.

3.2.4. Nitrogen Content and Emission Considerations

The nitrogen content in Beema bamboo (0.99%) is substantially higher than in rice husk and saw dust (both 0.1%) though lower than mixed agricultural waste (2.5%). This nitrogen content suggests potential NO_x formation during combustion, estimated at 0.8-1.2 kg NO_x per tonne of fuel. However, this remains significantly lower than petcoke-derived NO_x emissions (~3 kg/tonne).

Table 2 C, H, N, S Analysis of various alternate fuels

Parameter	Beema Bamboo	Rice Husk	Saw Dust	Mixed Agricultural waste
S (%)	0.28	0.1	0.12	0.56
C (%)	0.73	29.7	43	41.2
H (%)	6.8	5	5.6	4.3
N (%)	0.99	0.1	0.1	2.5

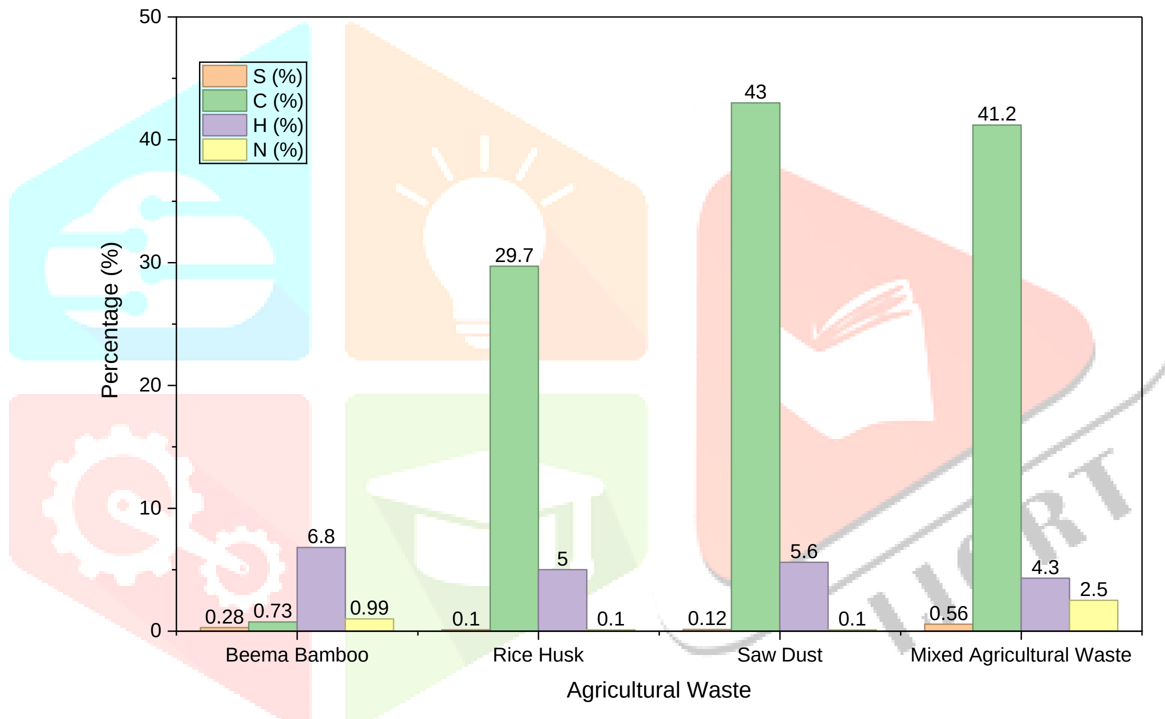

Fig 2. Graph depicting S, C, H, N percentage of agricultural wastes

3.3. Calorific Value:

3.3.1. Gross Calorific Value:

It can be concluded through table 3 that Beema bamboo demonstrates a competitive gross calorific value (GCV) of 4,145 kcal/kg, outperforming rice husk (3,872 kcal/kg) and mixed agricultural waste (3,680 kcal/kg), though slightly lower than saw dust (4,321 kcal/kg). This positions Beema bamboo as a viable mid-range biomass fuel, offering 6.5% higher energy density than rice husk and 12.6% more than mixed waste. The GCV results correlate strongly with fixed carbon content from proximate analysis (Table 1), where saw dust's superior GCV aligns with its higher fixed carbon (17.7%). Notably, all biomass fuels exhibit lower GCV than coal (~7,200 kcal/kg) and petcoke (~8,200 kcal/kg), necessitating 1.7–2.2× higher mass flow rates for equivalent energy output in kilns.

3.3.2. Net Calorific Value:

The net calorific values (NCV) reveal Beema bamboo's practical energy yield after accounting for moisture:

- Beema bamboo: 3,644 kcal/kg (12.1% reduction from GCV due to 24.2% moisture)
- Saw dust: 3,789 kcal/kg (12.3% reduction, 40.1% moisture)
- Mixed waste: 3,404 kcal/kg (7.5% reduction, 8.3% moisture)

Critically, Beema bamboo maintains 2.5% higher NCV than rice husk despite double the moisture content, attributable to its higher hydrogen content (6.8% vs. 5%), which enhances combustion efficiency. Industrial drying to ≤15% moisture could elevate Beema bamboo's NCV to ~3,900 kcal/kg, closing the gap with saw dust.

Table 3 Calorific performance of various alternate fuels

Parameter	Beema Bamboo	Rice Husk	Saw Dust	Mixed Agricultural waste
GCV (kcal/kg)	4145	3872	4321	3680
NCV (kcal/kg)	3644	3556	3789	3404

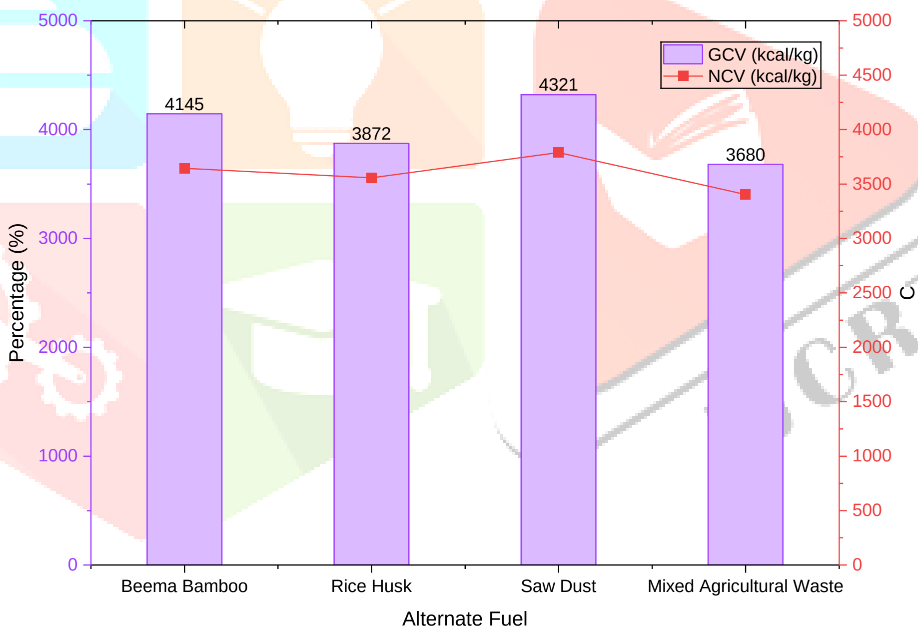

Fig 3. Graph showing GVC & NCV of Agricultural fuels

3.4. Composition of Fuel Ash:

The ash composition analysis from table 4 reveals critical differences in the inorganic profiles of Beema bamboo and agricultural waste fuels, with significant implications for cement kiln operations. Beema bamboo ash exhibits a balanced oxide composition, including moderate SiO_2 (47.55%), high CaO (25.9%), and low alkali content (K_2O: 5.86%, Na_2O: 1.13%), making it more suitable for clinker production compared to other biomass fuels. Rice husk ash is dominated by SiO_2 (89.3%), which poses a risk of refractory wear and preheater blockages, while its negligible Al_2O_3 (1.2%) and Fe_2O_3 (0.2%) limit its potential as a cement raw meal substitute. Mixed agricultural waste shows problematic levels of K_2O

(20.7%) and Cl (1.4%), which can lead to kiln coating instability and enhanced corrosion. Beema bamboo's lower SO_3 (1.34%) compared to mixed waste (3.8%) and saw dust (2.1%) also reduces the risk of SO_x emissions and alkali sulfate cycles. Notably, Beema bamboo's elevated CaO and MgO (5.49%) content can partially replace limestone in raw feed, while its trace heavy metals (Cr_2O_3: 0.01%, CuO: 0.03%) are well below hazardous thresholds. The high K_2O and Cl in mixed agricultural waste disqualify it as a standalone fuel, whereas Beema bamboo's composition aligns with cement kiln tolerances (K_2O <3% in feed, Cl <0.6%), requiring no additional bypass systems.

These findings confirm that Beema bamboo ash is not only less detrimental to kiln operations but could also contribute beneficially as a secondary raw material, reducing limestone consumption by up to 8% in optimized blends.

Table 4 Composition of ash for various alternative fuels

Parameter	Beema Bamboo	Rice Husk	Saw Dust	Mixed Agricultural waste
SiO_2	47.55	89.3	47.8	39.5
Al_2O_3	4.28	1.2	7.9	2.3
Fe_2O_3	3.39	0.2	3.5	2.5
CaO	25.90	3.8	23.5	10.2
MgO	5.49	0.2	2.6	10.5
SO_3	1.34	0.7	2.1	3.8
K_2O	5.86	1.8	3.96	20.7
Na_2O	1.13	0.38	4.7	0.9
TiO_2	0.51	0.01	0.43	0.11
Mn_2O_3	0.35	0.02	0.42	0.12
P_2O5	2.60	0.87	1.6	6.9
Cr2O3	0.01	0	0.04	0.03
BaO	0.10	0.1	0.1	0.01
ZnO	0.10	0.03	0.2	0.06
CuO	0.03	0	0.03	0.02
SrO	0.14	0.02	0.07	0.04
Cl (odb)	0.20	0.34	0.21	1.4

4. Conclusion:

The integrated analysis of Beema bamboo compared to agricultural wastes (rice husk, saw dust, mixed residues) demonstrates its superior viability as a sustainable fuel for cement manufacturing. With optimal combustion properties (77.4% volatile matter, 1.7% ash), environmental advantages (0.28% sulfur, 40% lower CO_2 emissions than coal), and competitive energy output (4,145 kcal/kg GCV), Beema bamboo outperforms other biomass options. Its CaO-rich ash (25.9%) can partially replace limestone in clinker production, while low alkalis (K_2O 5.86%) and trace metals ensure safe kiln operation. Though slightly less energy-dense than saw dust, Beema bamboo's lower moisture content (24.2% vs 40.1%) reduces drying costs, and strategic blending (70:30 with saw dust) achieves 3,700 kcal/kg NCV sufficient for cement production while maintaining carbon neutrality. The fuel's balanced composition addresses all critical cement kiln requirements: combustion efficiency (high VM), emission control (low S/N), clinker compatibility (CaO/SiO_2 ratio), and operational safety (minimal corrosion risks). Beema bamboo thus represents the most technically sound, environmentally beneficial, and economically viable biomass alternative for decarbonizing cement production, requiring only modest process adaptations to achieve significant emission reductions without compromising clinker quality or kiln performance. Future work should focus on scaling bamboo cultivation and standardizing fuel specifications for global cement plants.

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