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Biomass As A Renewable Fuel: An Analytical Approach Toward Sustainable Energy Transition

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Abstract
The global energy landscape is undergoing a paradigm shift toward sustainability, driven by the depletion of fossil fuel reserves and the adverse environmental impacts of conventional energy sources. Biomass, as a renewable and carbon-neutral resource, has emerged as a promising alternative fuel capable of contributing significantly to the sustainable energy transition. This study presents a comprehensive analytical investigation into the utilization of biomass for energy generation, emphasizing its potential, performance characteristics, and role in reducing greenhouse gas (GHG) emissions. The study carefully looks at different types of biomass feedstocks, like waste from farms and forests, as well as organic waste from cities. It does this by testing their physical and chemical qualities, as well as their energy content and how well they can be converted using thermochemical and biochemical methods. When compared to traditional fossil fuels, biomass has benefits in terms of being able to be used over and over, being renewable, and having low lifetime emissions. The study also looks at the latest technical advances in systems that turn waste into energy, like gasification, pyrolysis, and anaerobic digestion, and how well they work in both centralised and decentralised energy models. To give a full picture of biomass use, policy consequences, economic feasibility, and merging problems within current energy systems are also talked about. The results show that biomass can be used with other green energy sources to help reach goals for energy diversity, rural lighting, and reducing climate change. At the end of the study, there are practical suggestions for how to improve the use of biomass by creating policies that are helpful, spending money on research and development, and encouraging public-private partnerships. This way of looking at things not only supports biomass as a green fuel, but it also gives lawmakers, experts, and industry leaders useful information they can use to speed up the world's transition to a sustainable energy future.
Keywords: *- Biomass utilization, renewable energy, sustainable fuel, energy transition, carbon neutrality*

INTRODUCTION

There's a pressing want to check out safe and green strength choices due to the rising demand for energy and the growing concerns about climate alternate, environmental damage, and the loss of fossil gasoline materials. In this situation, biomass has come to be one of the maximum capacity sustainable electricity sources that may be used instead of fossil fuels to reduce down on greenhouse gasoline (GHG) pollutants and help the world's electricity device end up much less carbon-based. Biomass is made from organic materials like farm garbage, woodland via-merchandise, and trash from cities. It has many benefits, consisting of being easy to find, carbon-impartial, and usable in many distinctive conversion procedures. Biomass energy can be used in two exclusive methods: thermochemically (via burning, gasification, and pyrolysis) and biochemically (thru anaerobic digestion and fermentation). Every has its very own execs and cons. Biochemical tactics can flip biomass without delay into biofuels that may be used in cutting-edge transportation and manufacturing systems [1, 2]. Thermochemical procedures, alternatively, can flip biomass without delay into heat or power. Latest improvements in those conversion technologies have made biomass a sensible and aggressive choice to fossil fuels. Many studies have proven that it has the capacity to greatly reduce carbon emissions [3, 4].

But, even though biomass has numerous ability, the use of it on a large scale as an inexperienced energy supply is not easy. These consist of issues with getting the product, transporting it, the price of processing it, and the way nicely conversion methods work. To make sure it allows attain sustainability dreams, adding biomass to present day strength structures and looking at its component in a bigger electricity shift diagram want to be carefully notion out [5, 6]. As hobby in biomass grows, distinctive rules have been made to help cast off those problems and encourage extra people to use biomass strength [7]. Those policies include funding, tax breaks, and research funds. The principle aim of this examine is to describe how biomass may be used as an inexperienced gasoline, with a focal point on how it would assist with the shift to sustainable energy. This have a look at appears on the extraordinary forms of biomass feedstocks, processing strategies, and the financial and environmental consequences of the usage of biomass. The purpose is to give a complete picture of ways biomass can assist clear up the world's power troubles. This examine additionally desires to check out how the usage of biomass is related to larger environmental goals like preventing weather alternate and making sure there's sufficient strength for everybody. It additionally desires to investigate what role authorities and enterprise can play in speeding up the adoption of biomass. This paper tries to present a full photo of biomass as a sustainable power source by carefully looking at preceding research, new technology, and adjustments in authorities' policies. The consequences are anticipated to feature to the current discussion approximately the future of inexperienced strength and assist the push for an extremely low-carbon, lengthy-term power future [8, 9].Using biomass has large social and economic advantages, specifically in rural and agricultural areas, similarly to being accurate for the earth. Due to the fact biomass substances are unfold out, they work nicely for small and medium-sized energy production devices. These devices can assist local organizations grow, create jobs, and enhance power get right of entry to in areas that do not have it [10]. Including biomass strength projects to contemporary farming and forest activities also makes it simpler to deal with organic waste, which solves the hassle of where to position waste at the same time as additionally making useful strength products like biochar, biogas, and bioethanol [11, 12]. With the right deliver chain management and infrastructure development, biomass may be a stable a part of mixed green electricity structures. This would make electricity safety higher and lessen our reliance on fossil fuels which are added in from different nations. additionally, lifespan research have proven over and over that fuels made from biomass could have internet-zero or even net-terrible carbon emissions if they are treated and sourced in a way that does not harm the environment. That is particularly authentic when combined with carbon capture and storage (CCS) technologies [13]. Those many advantages display how essential it is to push forward with study, new ideas, and government assist to get beyond the present day issues and absolutely utilise biomass in a destiny of sustainable electricity.

METHODOLOGY

2.1 Elemental Composition of Biomass Pellets by Ultimate Analysis

The factors that make up biomass pellets were determined the usage of last analysis, which offers an in depth quantitative assessment of the main factors: carbon (C), hydrogen (H), nitrogen (N), sulphur (S), and oxygen (O). Those factors are imperative for perception how biomass burns and what its gasoline houses are. In line with ASTM D5373 and D4239 pointers, this test was once achieved with a CHNS/O elements analyser. At the beginning, representative samples of biomass pellets crafted from feedstocks like farm waste, sawdust, and natural waste pellets had been gathered from certified dealers. Earlier than the assessments, every pattern used to be dried within the air to get the natural wetness degree underneath 10%. After the samples have been dried, they were floor in a lab-grade mill until the particles had been all of the same size, which was once much less than 250 micrometres. This decrease in size made positive that the debris have been all the identical length, that's essential for accurate burning all through the study. After the samples have been made, they have been put away in sealed, moisture-proof cases to preserve them from getting contaminated and to keep their integrity till they have been analysed. A precision microbalance with a resolution of 0.001 mg was used to weigh approximately two milligrammes of each ground biomass sample for the chemical analysis. The pattern was positioned right into a jar made of excessive-purity quartz and put into the CHNS analyzer's burning chamber. The burning came about in an oxygen-rich putting at temperatures between 950°C and a 1000°C. Carbon and hydrogen inside the sample have been burned at excessive temperatures, turning them into carbon dioxide (CO_2) and water vapour (H_2O), which were then discovered the use of thermal conductivity detectors (TCDs). Nitrogen more often than not came out as nitrogen fuel (N_2) or nitrogen oxides (NOx), which have been measured after the discount and separation steps. If sulphur used to be present, it used to be become sulphur dioxide (SO_2) and measured with an infrared (IR) display.Oxygen content was not measured directly by the instrument due to its complex detection mechanism. Instead, it was calculated by difference using the equation

$$O\ (\%) = 100 - (C\% + H\% + N\% + S\% + Ash\%)......................(1)$$

Where ash content was determined separately through proximate analysis.

Each sample was analysed in triplicate to ensure the precision and reproducibility of results. Standard calibration procedures were followed using certified reference materials such as benzoic acid or acetanilide. Instrument blanks were also run between successive samples to prevent cross-contamination and ensure measurement accuracy. The data obtained from the ultimate analysis were used to derive critical combustion parameters. One such parameter was the higher heating value (HHV), which was estimated using Dulong's empirical equation 2

$$HHV\left(\frac{kJ}{kg}\right) = 33.8 \times C + 144.2 \times \left(H - \frac{O}{8}\right) + 9.4 \times S................(2)$$

Where C, H, O, and S represent the mass percentages of carbon, hydrogen, oxygen, and sulphur, respectively. This calculated HHV provides an estimate of the energy potential of the biomass fuel. In addition, the elemental composition was also used to assess the stoichiometric air requirement and potential emission characteristics, supporting further environmental and combustion performance evaluations.

2.2 Proximate analysis of biomass pellets

We did a close have a look at of biomass pellets to find out their primary gasoline houses, along with the quantity of water, flammable matter, ash, and stuck carbon they contained. these elements are very essential for identifying how biomass burns, how efficient it is, and whether or not it is a great preference as an inexperienced gasoline supply. The stairs used on this have a look at had been based totally on fashionable strategies set by using the Bureau of Indian standards (IS) and the yank Society for testing and substances (ASTM). This made sure that the outcomes were reliable, could be repeated, and might be compared to outcomes from other biomass research. At first, the biomass pellets got here from neighborhood agricultural and industrial sources, along with makers of rice husk, sugarcane bagasse, and pellets made from sawdust. Samples had been air-dried to take away any wetness on the surface and then homogenised to ensure they were all of the equal. Then, they have been installed cases that kept air out and stored wetness out until they were examined. To get statistically correct results and reduce the danger of mistakes, all tests have been carried out three times. Approximately 1 gramme of the prepared biomass sample was once weighed out and installed a clean, dry crucible to find out how plenty water used to be in it. The sample was then heated in a hot air oven that was kept at 105 ± 2°C for one hour, that's what ASTM E871 and IS 1350 (element 1) say must be accomplished. The crucible used to be heated and then cooled in a desiccator to maintain it from absorbing water once more. It used to be then weighed once more. Equation 3 was used to figure out the amount of wet content by looking at how much weight was lost during drying.

$$Moisture\ (\%) = \{(W1 - W2)/W1\} \times 100................ (3)$$

The oven-dried sample was put in a closed container and fired in a muffle furnace at 950 20°C for 7 minutes, as per ASTM E872 and IS 1350 (Part 1). This was done to find the flammable matter. It was then put in a desiccator to cool down and weighed. The sample's flammable matter was what caused it to lose weight during this process, minus the amount of water it contained. The amount of flammable stuff was found using the equation 4.

$$\text{Volatile Matter (\%)} = \{(W2 - W3)/W1\} \times 100 \text{.................(4)}$$

To find out how an awful lot ash used to be inside the pattern, it was once heated in a muffle hearth at 750 25°C for one hour after the risky remember check. Standards ASTM D1102 and IS 1350 (component 1) were used for this step. The sample was cooled in a desiccator and weighed once more after the cooking technique was once over. The ash percentage, which used to be found the usage of equation 5, is the quantity of solid matter that was once left over after the hearth used to be out.

$$\text{Ash (\%)} = (W4/W1) \times 100 \text{.............................(5)}$$

Finally, the fixed carbon content, which represents the solid combustible residue remaining after the removal of moisture, volatile matter, and ash, was calculated by difference. This value was determined using the equation 6.

$$\text{Fixed Carbon (\%)} = 100 - (\text{Moisture} + \text{Volatile Matter} + \text{Ash}) \text{.............(6)}$$

Constant carbon is an important thing as it influences how properly the gasoline burns and how speedy it burns. We are able to completely understand the temperature behaviour and burning properties of the biomass pellets being studied way to this close-up studies. The data accumulated is important for figuring out how nicely those pellets work in strength-producing structures like combustion stoves, gasifiers, and co-firing units. This will help biomass grow to be a greater possible source of green power in the end.

2.3 Scanning Electron Microscope (SEM) analysis

One method this look at checked out the surface structure and microstructural functions of different biomass samples earlier than and after warmth conversion was with the aid of the usage of a scanning electron microscope (SEM). It is very important to apprehend the physical and molecular traits of biomass because they have got a direct effect on its response, the way it burns, and how properly it converts energy. The biomass samples, which have been in general farm waste and lignocellulosic substances, have been first dried in an oven at one hundred and five°C for 24 hours to take away any water that might have affected the first-class of the photos. The dried samples have been then finely ground and sieved to get debris with a size that used to be all below 250 μm so that the picture outcomes would be the identical on every occasion. Earlier than the SEM images have been taken, the samples have been covered with gold the use of a vacuum spark coater for approximately ninety seconds. This made them greater conductive and stopped them from charging up under the electron beam. We used an excessive-decision Scanning Electron Microscope (version: JEOL JSM-7600F) with a growing voltage of 15 kV to do the SEM imaging.

We took snap shots at low and excessive magnifications (from 100x to 5000x) to have a look at the surface texture, porosity, particle disintegration, and changes in form attributable to pre-remedy and heat approaches like pyrolysis and gasification.It was once very essential to locate changes inside the shapes of the uncooked biomass and samples that were dealt with as a way to figure out how the cellulose, hemicellulose, and lignin additives had been broken down. The SEM photographs showed huge changes within the floor functions, like cracks performing, the surface turning into rougher, and the increase of hollow structures, particularly in samples that had been heated to excessive temperatures. These modifications display that the surface region has grown, which would possibly make the biomass greater reactive and efficient for the duration of conversion processes. The thorough SEM evaluation gave us useful records about how biomass changes structurally, which helped us figure out how microstructural developments are associated with thermochemical behaviour. After accumulating SEM information, it was once blended with outcomes from different exams, like proximate evaluation, Fourier-remodel infrared spectroscopy (FTIR), and thermogravimetric evaluation

(TGA), to create a full photograph of biomass as a green fuel.

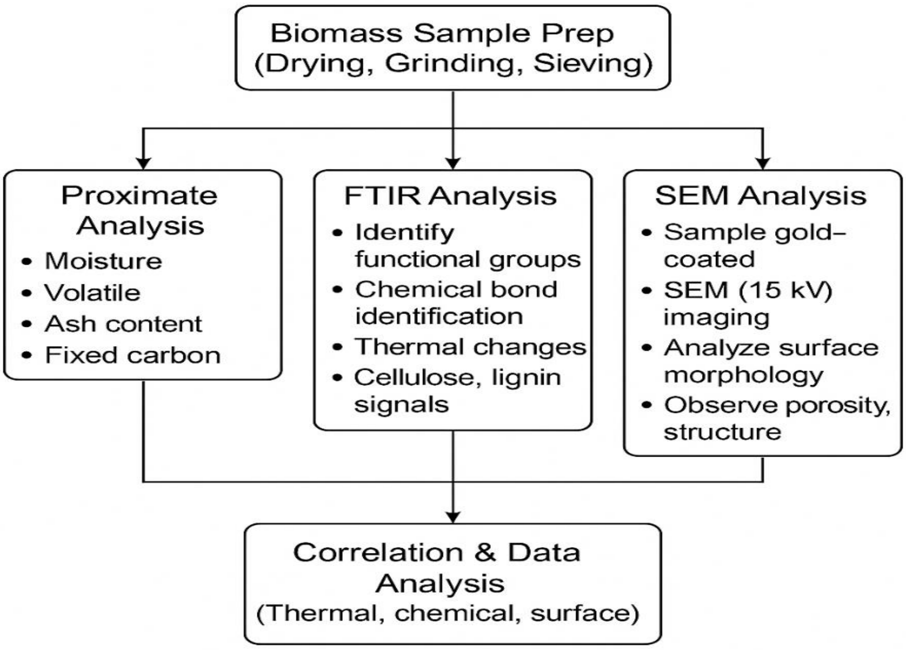

Figure 1: Flowchart of Biomass Characterization Methods Using Proximate Analysis, FTIR, and SEM Techniques

RESULT AND DISCUSSION

Pellet Composition and Feedstock Variation

Figure 2 shows the chances of garden Biomass (GB), Municipal strong Waste (MSW), Cow Dung (CD), Agricultural Straw (AS), Agro-business Nut Shells (ANS), and Grass garden (GL) that have been used to make five one of a kind biomass pellet types. pattern five has lots of GB (75%), which means it has a profile this is excessive in lignocellulosic substances which are right for burning balance. Pattern 14 however has a number of MSW (75%), which suggests that it's miles an aggregate of different kinds of town waste that is probably energy-dense. Among samples 6 and seven, there's a change from GB to a more numerous blend with higher amounts of CD, AS, and GL. sample sixteen, that's mainly made from MSW (45%), plus important quantities of CD, AS, ANS, and GL, is a nicely-balanced mix that is conjectured to enhance burning while decreasing ash content material and pollution. these variations in make-up show how essential it's miles to mix feedstocks in a smart recognitions to make biomass pellets which might be best for one of a kind electricity makes use of.

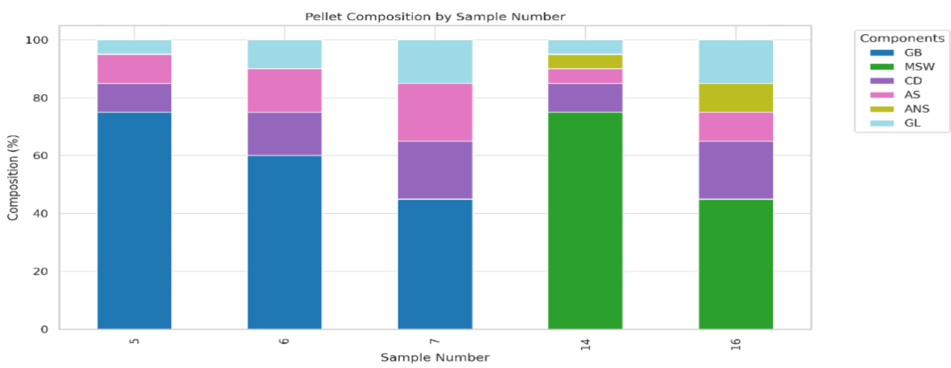

Figure 2. Pellet Composition by Sample Number showing distribution of GB, MSW, CD, AS, ANS, and GL in biomass pellets.

Elemental Composition: Impact on Combustion Potential Figure 3 shows that the carbon (C), hydrogen (H), nitrogen (N), sulphur (S), and oxygen (O) contents of the samples vary greatly when analysed by elements. Sample 5 has the most GB and the most carbon (41.83%) and hydrogen (6.34%), which means it has a good possibility for burning. On the other hand, Sample 6, with a greater share of fibrous and nutrient-rich residues like CD and GL, has a reduced carbon value (28.75%). Oxygen content, ranging from 60.45% to 89.77%, plays a critical role in determining the overall fuel quality, with high oxygen often correlating with lower energy density. The presence of nitrogen and sulfur across all samples remains within environmentally acceptable limits, with maximum values of 1.80% and 0.83%, respectively. This suggests that all formulations are suitable for combustion without significant risk of NOx or SOx emissions.

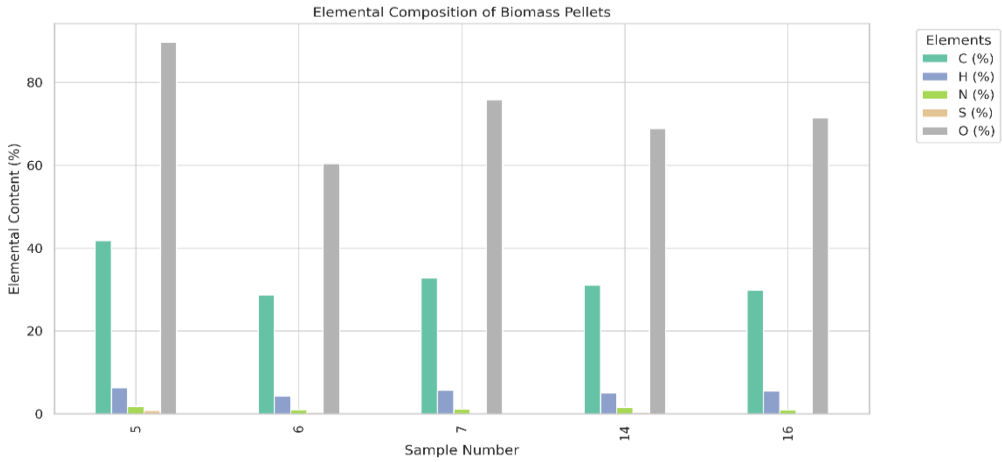

Figure 3. Elemental Composition of Biomass Pellets showing C, H, N, S, and O content across

different samples.

Higher Calorific Value (HCV) Assessment

The calorific performance of each biomass sample, as depicted in Figure 4, highlights the influence of compositional and elemental factors on energy yield. Sample 14, dominated by MSW, delivers the highest HCV of 5772.90 Cal/gm. This may be attributed to the presence of high-energy fractions in MSW such as paper, plastics, and food waste, which combust efficiently despite their heterogeneous nature. In contrast, Sample 5, although high in carbon, exhibits the lowest HCV (3723.60 Cal/gm.), likely due to excessive oxygen content (89.77%), which limits net heat output. Samples 6, 7, and 16 all deliver competitive HCVs in the range of 4450–4700 Cal/gm., suggesting that co-pelletization with agro-residues and organic matter can provide effective energy solutions for decentralized applications.

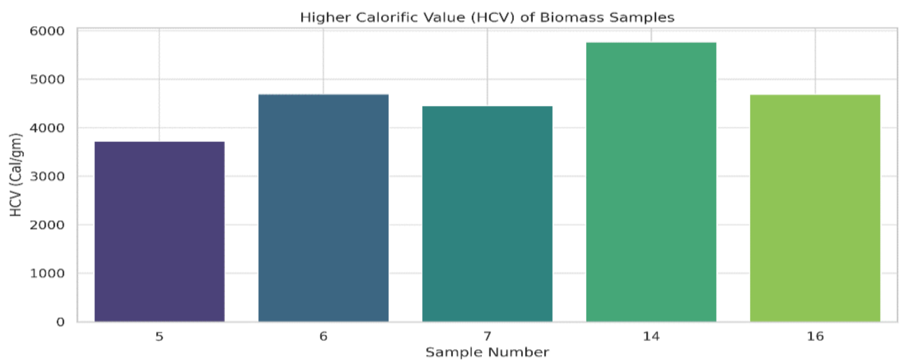

Figure 4. Higher Calorific Value (HCV) of Biomass Pellets in Cal/gm. across all samples.

Proximate Analysis of Biomass Pellets

The proximate composition of the biomass pellet samples is illustrated in Figure 5, highlighting the distribution of volatile matter (VM), moisture content, ash content, and fixed carbon (FC) across five representative samples (Sample Nos. 5, 6, 7, 14, and 16). These factors are basic ways to judge the quality of the fuel, how well it burns, and how quickly it breaks down at high temperatures. The amount of flammable stuff in Sample 5 was 23.64% and in Sample 7 it was 36.42%. The VM rates of samples 6, 7, and 16 were much higher, which means they could devolatilize quickly during heat processing. A lot of flammable matter means that the substance is more reactive and easier to light, which is good for thermochemical processes like gasification and pyrolysis. Sample 5, on the other hand, had the lowest VM, which means it is made of a material that burns more slowly and tends to keep burning for a long time. Moisture content across the samples varied from 9.23% (Sample 14) to 18.39% (Sample 7). Elevated moisture levels, as observed in Sample 7, can adversely affect combustion efficiency due to the additional energy required for drying. Samples with lower moisture contents, such as Samples 5 and 14, are more favorable in practical combustion applications, as they reduce the preheating energy demand and enhance net calorific value. Ash content was observed to be highest in Samples 7 and 16 (36.41% and 35.60%, respectively), whereas Sample 5 had the lowest ash content (23.63%). Elevated ash concentrations are undesirable, as they contribute to operational challenges such as clinker formation, fouling of heat transfer surfaces, and increased solid residue handling. The low ash content in Sample 5 suggests improved combustion quality and reduced post-processing requirements. Fixed carbon content—a crucial parameter for sustained heat release—was highest in Sample 5 (43.16%) and lowest in Sample 7 (8.78%). A higher fixed carbon content indicates a greater proportion of combustible carbon remaining after devolatilization, which enhances the heating value and long-term combustion stability. Sample 5's high FC and low ash content imply superior fuel characteristics compared to the other samples evaluated.

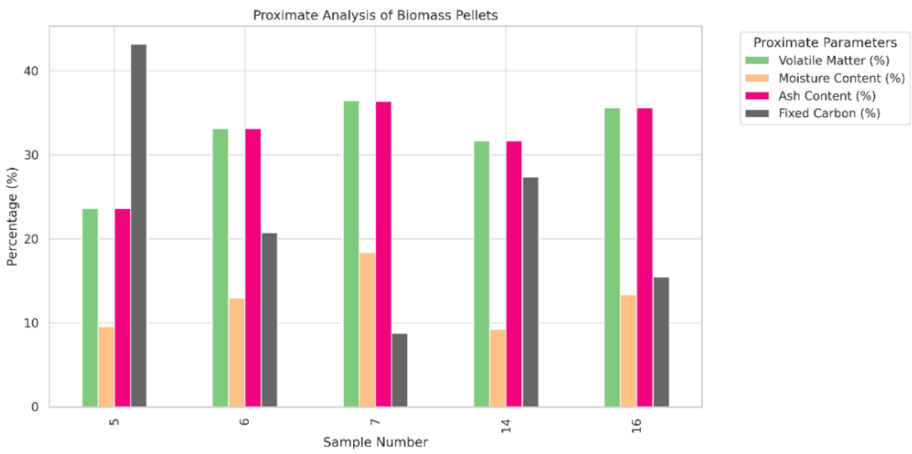

Figure 5. Proximate analysis of biomass pellet samples.

VM/FC Ratio Analysis

The ratio of risky count number to constant carbon (VM/FC) is a key indicator of fuel reactivity and thermal decomposition characteristics. Figure 6 suggests how the VM/FC ratio changed among the 5 samples. A high VM/FC ratio implies that volatiles are extra not unusual, which means that the fuel will burn faster. On the other hand, a low ratio implies that there's greater constant carbon inside the gas, which means that that it's going to burn greater slowly and for an extended time. The samples' VM/FC fees were observed to be 0.fifty five for sample five, 1.60 for sample 6, four.15 for sample 7, 1.16 for pattern 14, and 2.30 for sample 16. Sample 7 had the best VM/FC ratio, which means it had a variety of volatile carbon and not tons fixed carbon. This makes me think it might work nicely for

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obligations that want fast warmness breakdown, like flash pyrolysis. In actual life, though, its excessive ash and moisture stage may cancel out those advantages. The sample with the bottom VM/FC ratio, pattern 5, on the other hand, burned slowly and had an excessive energy density. it's miles higher for controlled burning settings where longer holding time and warmth performance are important because it has a higher constant carbon content material and much less ash yield. The VM/FC fees for samples 6, 14, and sixteen have been within the center, because of this that they had a more balanced burning profile. Those samples may go nicely with a variety of thermochemical conversion technologies. Sample 14 is mainly useful because it has low ranges of wetness and middling stages of ash.

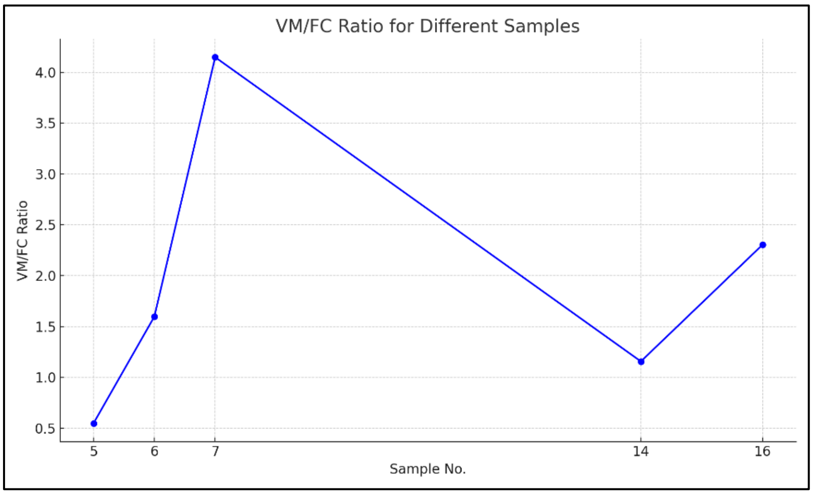

Figure 6. Volatile Matter to Fixed Carbon (VM/FC) ratio for different biomass pellet samples

Comparative Evaluation

Evaluating the samples' close by factors and VM/FC ratios suggests that they behave in one-of-a-kind approaches. Sample 5 is the maximum thermally efficient and stable gas for burning. It may be used in conditions that want to launch heat slowly and over a long period of time. Pattern 7 then again, even though it has quite a few volatiles and is reactive, won't be as excellent as it has too much ash and moisture that could make the procedure much less efficient and shorten the lifestyles of gadget. While we study the VM/FC ratio together with the close by makeup, you could get a terrific idea of how thermally reactive biomass pellets are and whether they are true for sure strength conversion processes. This blended technique makes it less complicated to pick out the right feedstock for structures that use burning or gasification.

Surface Morphology Analysis Using SEM

The 5 most thermally green biomass pellet combos have been selected primarily based at the calorific values proven in table 4.2. They have been then sent for a Scanning Electron Microscopy (SEM) evaluation in their microstructure. Floor imaging was once used on pattern Nos. 5, 6, 7, 14, and sixteen to look at their structural functions and the way the debris are bonded to every other. The SEM pix that go with them can be located in Figures 4.5 to 4.9. A lot of humans use SEM to study the shape of the surface of stable items. A slim move of excessive-power electrons is moved across the floor of the pattern. Those electrons integrate with atoms, creating secondary electrons, backscattered electrons, and different symptoms. Those signs and symptoms tell us loads about the fabric's surface roughness, porosity, and how frivolously its components are disbursed. In terms of biomass pellets, SEM makes it less complicated to check the great of the bond, the uniformity interior, and the structure stability. Those are all matters which have an immediate impact on how lengthy the pellets ultimate and the way they burn. In keeping with the SEM facts, the surface roughness of all 5 samples is mostly easy, and the

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debris inner are unfold out lightly. However, there are huge modifications among examples in the nice of the binding and the pores of the surface. This shows that the solid trash and binder interaction are not always working as well as they should.

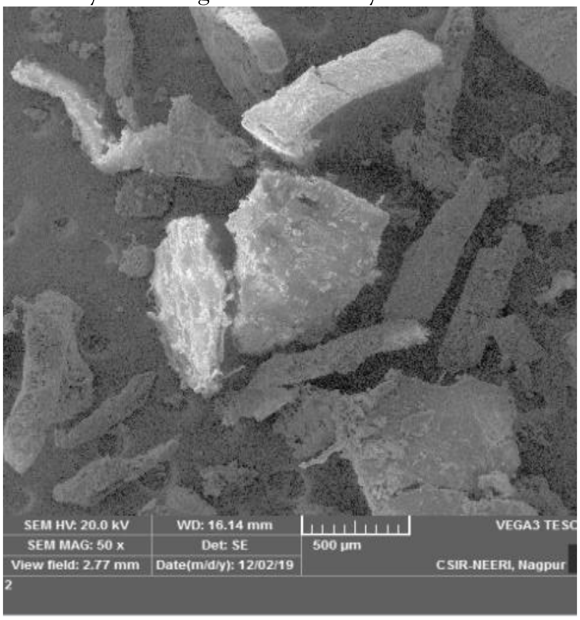

Figure 7. SEM image of Sample No. 5 showing a relatively porous surface and weak inter-particle bonding.

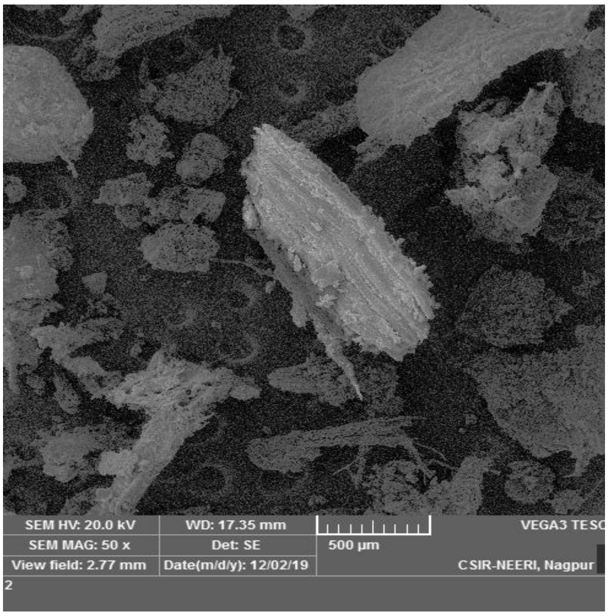

Figure 8. SEM image of Sample No. 6 indicating moderate consolidation with reduced surface voids.

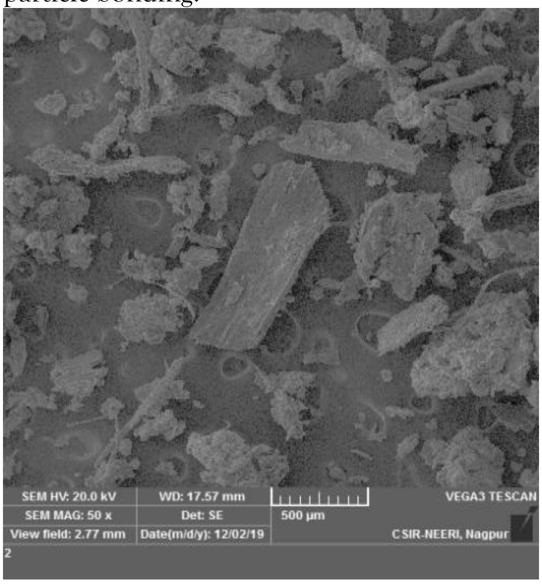

Figure 9. SEM image of Sample No. 7 highlighting fibre interlinking and strong particle agglomeration.

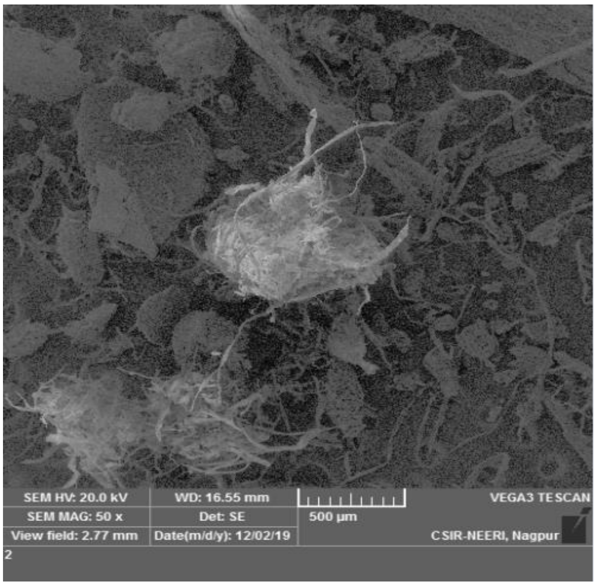

Figure 10. SEM image of Sample No. 14 showing dense surface morphology and efficient particle binding.

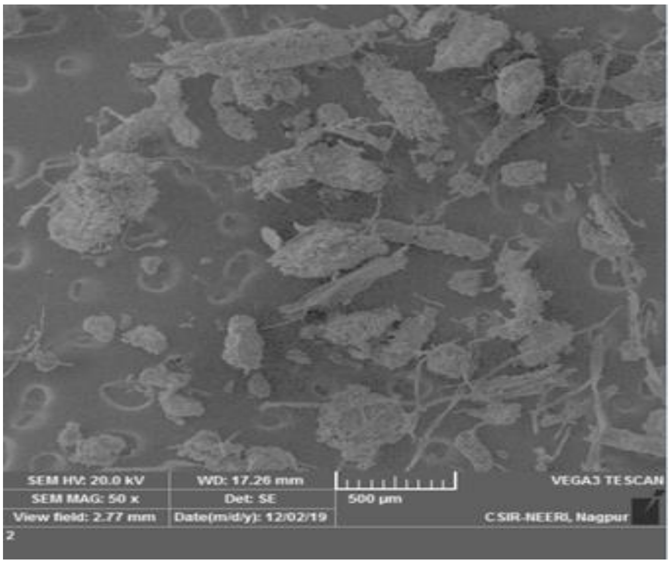

Figure 11. SEM image of Sample No. 16 illustrating high degree of cross-linking and fiber bridging.

MORPHOLOGICAL OBSERVATIONS

Figure 4.5 (Sample 5): The surface structure of Sample 5 shows moderate porosity and relatively weak bonding. The presence of voids and micro-cracks suggests that the binding among particles is not optimal. This could be attributed to insufficient binder action or inadequate compaction during pellet formation. Figure 4.6 (Sample 6): Sample 6 exhibits a more consolidated structure with fewer visible voids, indicating better particle-particle adhesion. The surface appears denser and the interstitial spaces are minimized, which is favorable for enhancing mechanical strength and thermal performance. Figure 4.7 (Sample 7): A well-defined network of fiber strands is observed, indicating enhanced inter-particle connectivity and binding. The matrix shows signs of agglomeration and cross-linking, both of which are desirable features in pellet manufacturing as they improve structural integrity. Figure 4.8 (Sample 14): The SEM micrograph reveals densely packed particles with evident fiber bridges contributing to the binding mechanism. The homogeneity and minimal porosity suggest that the pellet is structurally sound, with a high degree of compactness, likely leading to improved calorific efficiency and lower friability. Figure 4.9 (Sample 16): Similar to Samples 7 and 14, Sample 16 exhibits significant fiber interlinking and minimal void formation. The morphology indicates efficient cross-linking and a high level of agglomeration, both indicative of strong particle cohesion and optimized binder performance.

Interpretation and Implications

The SEM analysis clearly demonstrates that the physical binding of the biomass components is highly dependent on both the material composition and the binder effectiveness. The bonding occurs primarily through the formation of solid bridges, and in some cases, aided by fiber entanglement, as seen in Samples 7, 14, and 16. These samples exhibited superior morphological features such as enhanced inter-particle cohesion, fewer voids, and better matrix uniformity parameters critical to improving pellet density, durability, and combustion characteristics. On the contrary, Samples 5 and 6, though thermally efficient, displayed relatively weaker bonding, as evidenced by higher surface porosity and less pronounced fiber bridging. For such compositions, the use of more effective binders or optimization of pelletizing parameters (e.g., pressure, temperature, moisture content) is recommended to improve internal cohesion and reduce structural flaws. Overall, SEM microstructural characterization validates the importance of both material selection and binding strategy in achieving high-performance biomass pellets. The morphological uniformity observed in the best-performing samples aligns with their favourable proximate and calorific properties, confirming the critical role of structural integrity in enhancing biomass fuel quality.

CONCLUSION

This study systematically evaluated the potential of municipal solid waste (MSW) as a renewable energy source through palletisation, offering an environmentally sound and technically feasible alternative to conventional waste disposal practices. The study looked at the thermochemical and physical features of biomass pellets made from sixteen different types of MSW. The results support the idea that smart mixing and palletisation can greatly increase the energy potential of MSW, even though it is not a very good fuel on its own. The following important findings and trends were found. The successful creation of solid fuel cubes from different types of MSW shows a hopeful way to turn trash into something useful. This method not only cuts down on waste, but it also offers a long-lasting, clean energy source. After being treated, the pellets have enough structural stability to be used for storage, moving, and burning. Samples 5, 6, 7, 14, and 16 had the highest calorific values out of the 16 that were studied, making them the best choices for further study. The samples always had a low moisture content (≤15%), a modest amount of ash, and high amounts of volatile matter and fixed carbon, all of which improve the performance of burning. The chemical study showed a good carbon-to-hydrogen ratio and low levels of nitrogen and sulphur, which means the fuel burns better and produces less NO_x and SO_x. The trends in the VM/FC ratio across samples led to good burning properties. Higher values meant the mixture was less volatile and easier to light. These findings are substantiated by SEM analysis, which revealed variations in particle bonding, fiber interlinking, and void formation. Samples 7, 14, and 16, in particular, showed dense structures and pronounced inter-particle bridging, implying enhanced binder efficiency and mechanical stability. The improved calorific properties and structural robustness of the pellets make them suitable for co-firing in industrial boilers, cement kilns, and power plants. However, their application remains limited in high-temperature industrial processes (e.g., metal fabrication, glass production) where the heating values of biomass pellets are inadequate. Despite their potential, barriers such as inconsistent waste segregation, limited public awareness, emission concerns, and financial constraints at the municipal level still challenge widespread adoption. From a broader perspective, this study emphasizes the critical role of decentralized pellet production facilities in urban solid waste management frameworks. By integrating pelletization within municipal waste treatment operations, cities can transition toward a circular economy model, reducing landfill dependency while contributing to renewable energy targets. The analytical insights from this study validate biomass pelletization as a technically sound, economically feasible, and environmentally responsible strategy for MSW utilization. Future efforts should focus on optimizing binder formulations, automating waste segregation, and establishing regulatory frameworks that support large-scale deployment of waste-to-energy systems.

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