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# Torrefaction of Commonly Disposed Agricultural Waste Biomass for an Improved and Sustainable Energy Future: A Review

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## ABSTRACT

Scientists and policymakers are continuously making techno-economic efforts to close the loop in the agricultural value chain by utilizing and maximizing agricultural wastes and their products. The rising issues of agricultural waste management significantly impact the ecosystem and impede environmental sustainability. Untreated and wrongly disposed agricultural residues are a major threat to health (human and animal), the economy, and a significant contributor to greenhouse gas emissions. However, this review extrapolates a resource efficiency technology to address the energy deficit by converting these sustainable waste resource sources to sustainable energy through a sustainable energy system. The torrefaction technique is a more energy-efficient thermochemical process to upgrade the biomass fuel quality. Studies on readily available and commonly disposed agricultural wastes valorised with their energy values, energy density and physicochemical properties were reported in this study, and their performances were compared with fossil fuel (coal and sub-bituminous coal) properties. The assessment brings to the submission that many agricultural wastes can be upgraded to comparable quality in performance via the torrefaction process. It further discovers that the synergy of certain additives and the optimization of process conditions, such as residence time, temperature, pressure, and gas carrier, could better upgrade the biofuel quality without major compromise on product yield.

## INTRODUCTION

Global warming concerns about the continuous rise in greenhouse gas emissions and massive depletion of fossil fuels such as coal, petroleum, and natural gas are major challenges of industrialization. In coal-fired plants, for instance, fossil fuel air pollution from the burning of a ton of coal generates 3.67 tons of $CO_2$, which is disastrous to human health and the environment. As predictions to hit 14 billion $t.y^{-1}$ by 2050 heighten, the adoption of alternative sources of energy that are sustainable and renewable has become a necessary demand (Acharya et al. 2012). Subsequently, a report from the International Energy Agency (IEA), shows that the press for bioenergy has risen four times over the decades, which is expected to capture over 17% of global energy by 2060 (Cross et al. 2021, Röder et al. 2020) The ready availability of bio-feedstock has given bioenergy a leverage over other renewable and alternative energies such as solar, wind, hydropower and geothermal. It is also seen to have the potential to mitigate the greenhouse effect, giving a win-win carbon credit and reducing biomass waste. Hence, combating the solid waste (SW) complex problem due to improper waste management practices causes environmental and health concerns (Abdullah et al. 2022).

## BIOMASS AND THE CONCEPT OF TORREFACTION-THERMOCHEMICAL PROCESS

Biomass is referred to as the biological material of plant and animal origin, alongside their waste and residues (Chew and Doshi, 2011). Biomass, an acclaimed carbon-neutral fuel, engages in the bio-cycle, and the $CO_2$ from its combustion is reinjected into the growth of new crops. It is a choice of sustainable fuel able to reduce net carbon emissions instead of fossil fuel (Chew and Doshi, 2011). However, this biomass is broadly divided into woody and non-woody biomass. Its short carbon cycle makes it a renewable energy source with low greenhouse gas emissions based on its $CO_2$ captured during photosynthesis. However, biomass is a good substitute/ alternative to coal for sustainable energy production. Its drawbacks are its non-homogeneity, moisture content, alkality, cost of mobility, grindability, and reduced energy density relative to coal.

The transformation of biomass to energy can be achieved through several routes, such as biochemical, mechanical, and thermochemical. Thermochemical processing is attractive and efficient in transforming biomass to energy as it captures a broader fuel feedstock. Its lower temperature requirement makes it a suitable energy technology (Chew & Doshi 2011). However, the process of torrefaction, known as mild pyrolysis, could mitigate the shortcomings of biomass (Acharya et al. 2015). According to Acharya et al. (2012), it is the decomposition of biomass leading to the release of volatiles, having its final product as solid fuel known as torrefied biomass/fuel. The thermochemical transformation of biomass helps to bring down the NOx and SOx emitted relative to fossil fuels (Gilbert et al. 2009).

According to Kumar et al. (2020), the two primary thermal pretreatment techniques to enhance biomass quality and improve their properties are wet and dry torrefaction. Although wet torrefaction is less frequent, both processes can be used to obtain hydrophobic, uniform, high-carbon, and densified energy solid fuel (Acharya et al. 2015). Dry torrefaction (DT) occurs within a low oxygen environment at temperatures ranging from 200 to 300°C for a duration of 30 to 60 min. (Acharya et al. 2013), at atmospheric pressure, whereas WT is a thermochemical conversion process in subcritical water. WT is the thermal treatment of biomass in water at temperatures of 180-265°C, spanning from about 5 min to hrs at pressures above 1 MPa (Yan et al. 2009).

All lignocellulosic biomass has relatively similar patterns of cell walls, although they might differ slightly based on their specific composition and biomass. It mostly comprises 20% fixed carbon and 80% volatile content on a dry basis. It is made up of (40-60 wt.%) cellulose, (10- 25 wt.%) lignin, and (20-40 wt.%) hemicellulose (Acharya et al. 2012). However, the process of torrefaction changes the composition of the biomass under varying conditions such as temperature, time, pressure, and the nature of the gas. This process alters the chemical composition and causes the breakdown of hemicellulose, cellulose, and lignin, as shown in Fig. 1, where the hydroxyl (OH) compound is breaking down, and the hydrophilicity is improved (Bridgwater et al. 2000).

The torrefaction process can be broadly categorized into three phases: size reduction, drying, and roasting (torrefaction) phase (Acharya et al. 2012). The uniform and fine biomass

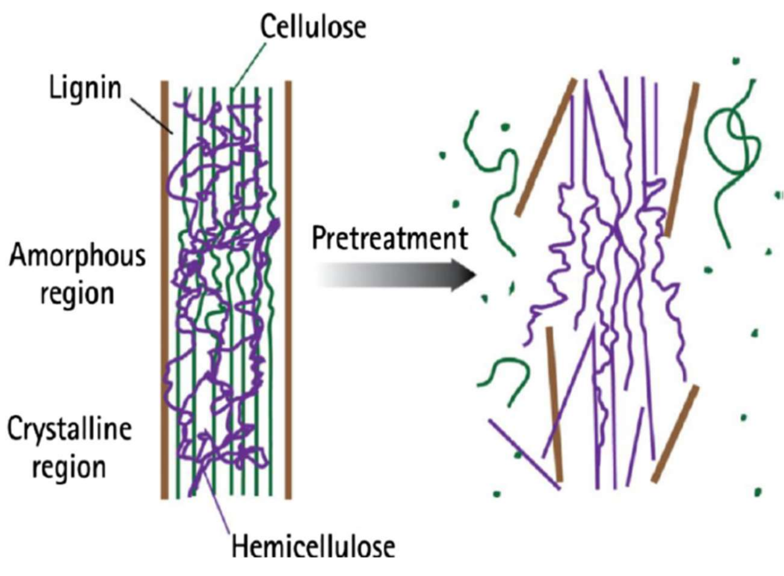


Fig. 1: Structure of biomass and thermal pretreatment(Acharya et al. 2012).

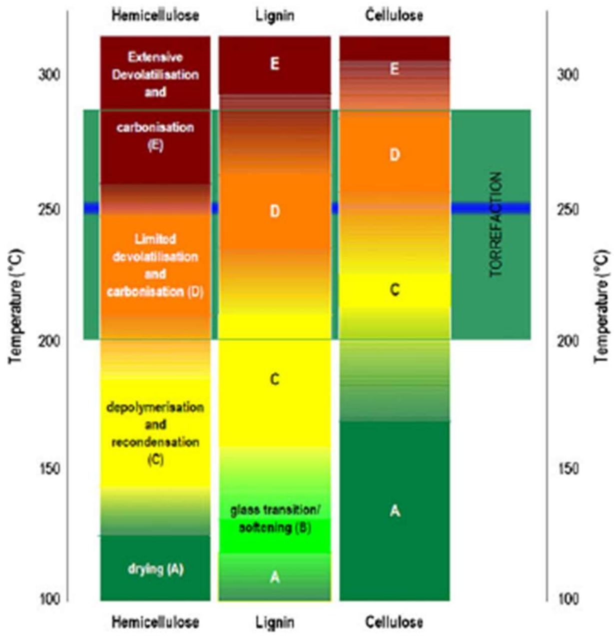


Fig. 2: Decomposition regimes of lignocellulosic material during thermal treatment (Uslu et al. 2008).

is subjected to drying to reduce moisture considerably and to liberate condensable and non-condensable gases and volatiles, before feeding into the torrefaction reactor. However, the extent of gases and volatiles liberated depends on the condition of torrefaction, especially temperature, leaving behind a solid product known as char or torrefied biomass (Ciolkosz et al. 2011). This process enhances the combustive characteristics of biomass for an attractive solid fuel suitable for heat energy applications.

Furthermore, it is worth noting that a series of decomposition reactions occurs in torrefaction, leading to a series of gaseous compound releases. This process alters the elemental compositions of the biomass and reduces the H/C, O/C ratio as hydrogen and oxygen content decline. It is also characterized by the destruction of hydroxyl (OH) groups in the decomposed biomass polymer structure, making it hydrophobic. At about 110°C, a major percentage of moisture is lost, and further temperature increases lead to polymeric structural decomposition, mainly hemicellulose. Between 250-300°C, more hemicellulose is decomposed, leading to massive weight loss at this stage with slight lignin and cellulose decomposition (Uslu et al. 2008, Rousset et al. 2011). Fig. 2 provides a typical representation of these processes with respect to temperature.

Typical biomass is constrained in widespread energy applications due to its inherent excessive moisture, volatile, oxygen content, lower density, low calorific value, and grindability (Singh et al. 2020). However, the torrefaction process helps to improve its physicochemical properties, such as achieving a reduction in volatile matter under a relatively lower heating temperature while most of the fixed carbon content remains. Fig. 3 provides a typical schematic of a torrefaction setup in a tube furnace, where a weighted biomass sample is loaded in the ceramic boat, and a nitrogen flow is supplied at a specified flow rate to the furnace for an assigned residence time. The hemicellulose content is the main and most reactive volatile matter decomposed during torrefaction, than the other two components, cellulose and lignin. As the torrefaction temperature advances, the mass yield is often seen to decline, and this is principally due to two major factors, which are moisture loss and thermal decomposition to form a volatile gaseous product such as $H_2O$, CO, $CO_2$, acetic acid and other organics (Poudel et al. 2015). This thermal decomposition occurs mainly on hemicellulose and lignin at torrefaction temperatures below 250°C; the partial decomposition of the cellulose later occurs as torrefaction conditions become more severe.

Energy yield is the measure of the ratio of actual energy retained after the torrefaction process to the initial energy content of the biomass (Bridgeman et al. 2008). Also, the combustibility of biochar can be assessed by using the fuel ratio, which is defined as the ratio of fixed carbon content to volatile matter content. This is a principal index to evaluate the potential/capacity of biochar fuel properties to replace coal. Also, according to Lin et al. (2025).

$$\text{Energy density} = \frac{\text{HHV of the torrefied sample}}{\text{HHV of the raw sample}} \quad \ldots(1)$$

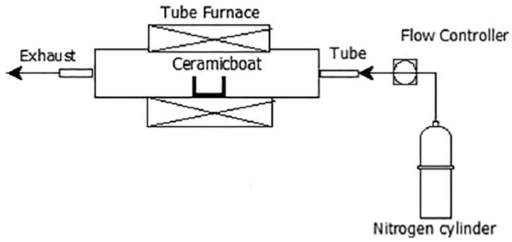


Fig. 3: Schematic of torrefaction setup (Patidar & Vashishtha 2021).

$$\text{Mass yield} = \frac{\text{Mass of torrefied sample}}{\text{Mass of raw sample}} \text{x } 100\%. \quad ...(2)$$

$$\text{Energy yield} = \text{Energy density x Solid yield} \quad ...(3)$$

Increased production of agricultural waste due to population growth and expanded agricultural practices has created an inexhaustible and sustainable agro-waste feedstock which can be converted into useful forms, such as biochar, biofuels, bio-coal pellets and other structural products. However, these wastes have not been effectively managed as they majorly litter the environment as pollutants instead of a bioresource for energy generation and a means for job creation. This review helps to appreciate the vast abundance of agro-waste in its varieties in the environment. It also showcases torrefaction as a low-cost and less energy-intensive route for bioenergy generation with emphasis on its operational process/ boundary conditions to achieve desirable efficient energy and optimal mass-energy yield balance. Furthermore, it also captures the techno-economic implications of selected torrefied agro-wastes.

The techno-economic analysis discusses the economic feasibility and technical performance of converting agricultural residues into more energy-dense and stable forms of biomass. This includes energy insecurity and environmental sustainability. The subject of temperature control, residence time and process design, carbon emission, waste reduction, cost-benefit analysis, market potential, agricultural waste type (rice husk, corn stalk and wheat straw, etc are among the contributors to the techno-economic feasibility of the torrefied agro-waste. Biomass torrefaction increases the energy content per unit weight (mass), and subsequent pelletization markedly improves the energy density per unit volume, thereby facilitating logistics throughout the supply chain.

## ROLE OF PROCESS TIME AND TEMPERATURE ON THE QUALITY OF AGRO-WASTE-DERIVED SOLID FUEL

The conversion of Walnut shell (WS) and pearl millet (PM) to solid biofuel was carried out by Abdullah et al. (2022). This was performed at a torrefaction temperature of (230-300)°C, times (30-90 min) and varying biomass composition. It is intended to upgrade their biochar properties to a equivalent comparable to coal. In this process, the highest biomass mass yield of 91% was achieved at (230°C, 30 min) and the lowest, which is 41% at (300°C, 90 min). It has a Gross calorific value (GCV) of 22 $MJ.kg^{-1}$ at the raw state and 27 $MJ.kg^{-1}$ at 300°C, accounting for a 22-59% HHV increase. At the optimal parameters of 260°C, 30 min, and a blend of (PM 70%, WS:30%), 80-88% yield was reported.

(Nigran Homdoung et al. (2019) examined the outcome of the torrefaction of wood chips and oil palm fronds under 200-400°C and a 20-60 min. It was clear that the energy properties and solid product were affected by the torrefaction time and temperature. No visible change in mass and energy yield was observed at 200C°C; 20-60 min for the mass yield of both oil palm fronds and wood chips. Hence, it was regarded as the optimum condition. The volatile% reduces as the torrefaction temperature moves from 200-400°C for both wood chips and oil palm fronds.

HHV of both biomass materials was improved to 17.65 $MJ.kg^{-1}$-24.86 for wood chips and 16.34 $MJ.kg^{-1}$-18.58 for oil palm fruit fronts, 20-30% higher than the original values. Oil palm fruit fronts have a higher ash content of up to 15% which was responsible for their lower HHV. The torrefaction process also helps achieve improved fixed carbon content of wood chips by 29-85% and oil palm front by 76-97%.

Yang et al. (2015) examined the fuel properties of wet torrefied biomass, namely the Humulus lupulus (HL), Plumeria alba and Calophyllum inophyllum L. (CIL) with varied component weights. The mass yield decreases as presented in Fig. 4a. 50.9% mass yield was obtained for CIL, 31.5% for PA and 26.5% for HL at 260°C. CIL has a greater mass yield due to its higher lignin content of higher decomposition temperature than hemicellulose and cellulose. It is hence considered more thermally stable than PA and HL. The HHV and energy yield increased from 17.5 $MJ.kg^{-1}$ to 25.3 $MJ.kg^{-1}$ for HL;17.7 $MJ.kg^{-1}$ to 25.7 $MJ.kg^{-1}$ for PA, and 18.4 $MJ.kg^{-1}$ to 23.6$MJ.kg^{-1}$ for CIL as the temperature advanced from 180 to 260°C. The HHV obtained at elevated torrefaction, which is 23.5 and 25.7 $MJ.kg^{-1}$ as shown in Fig.

4b, is comparable to that of some commercial coal. The H/C and O/C ratios of HL-260, PA-260, and CIL-260 were similar and closer to those of lignite, as shown in Fig. 4c**.**

Energy sorghum and sweet sorghum were torrefied under different temperatures (250, 275 & 300°C) for 30 min by Yue et al. (2017). Torrefied energy sorghum has 53.1-69.8% while torrefied sweet sorghum has 41.3- 64.7% solid yield at 250-300°C. The process of torrefaction helps to achieve an improvement in the HHV of energy sorghum from 17.33 MJ.kg$^{-1}$ (raw) to 23.62MJ.kg$^{-1}$ at 300°C, while

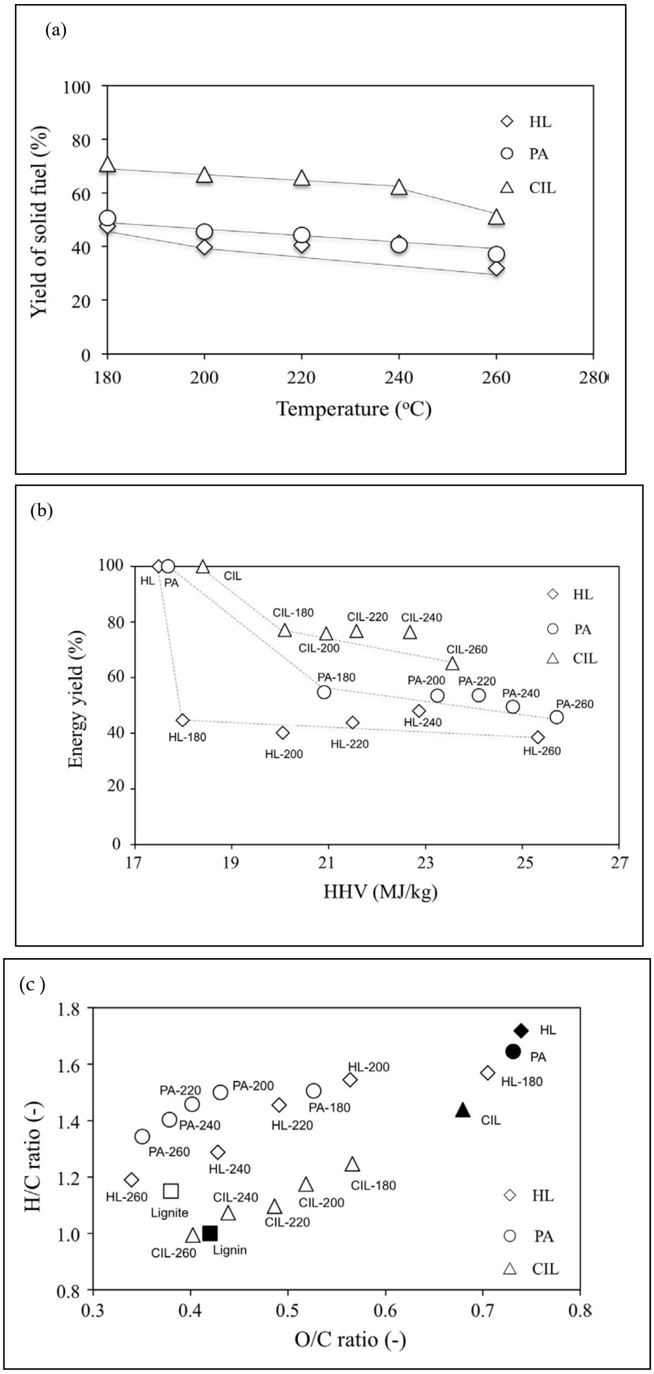


Fig. 4: (a) Mass yield of HL, PA, and CIL at various temperatures, (b) Energy yield against HHV for all the biomasses and their delivered solid fuel, (c) Van Krevelen diagram of the biomasses (Yang et al. 2015).

for sweet sorghum bagasse, 16.45 MJ.kg$^{-1}$ (raw) to 26.88 MJ.kg$^{-1}$ at 300°C.

Zhang et al. (2016a) carried out a wet torrefaction process on duckweed within 130–250°C to improve its fuel characteristics. The volatile content declined from 76.9%-60.0%, while the ash content improved from 7.65 to 19.9% within the range of 130-250°C. There was a notable decline in the mass yield from 64.8% -30.4% and the energy yield from 77.9%-40.1% across the torrefaction temperature range. Also, the energy density first shifted from 1.20 (D130) to -1.38 (D220)- 1.32(D250). Hence, 220°C is identified as the ideal reaction temperature for wet torrefaction of duckweed samples. The HHV improved from 14.34MJ.kg$^{-1}$, which is the raw sample, to 19.84 MJ.kg$^{-1}$ at D220 and then declined to a more severe temperature of 250°C. Wet torrefaction of duckweed at 250°C gave a closer H/C and O/c atomic ratio closer to lignite, which is indicative of improved solid fuel properties. Other features are improved C-content from 34.5% to 48.3%, reduced nitrogen and sulfur content.

The torrefaction of corncob, cotton stalks, and sunflower agricultural residues was performed by Akhtar et al. (2021) at 200-320°C; 10-60 min. Corncob has a mass yield of 63% and optimum GCV of 5444 kcal.kg$^{-1}$ at 290°C, 20 min. Torrefied cotton ball has optimal GCV of 4481 kcal.g$^{-1}$ at 270°C, 30min. An optimum condition at 260°C, an energy value of 4370 kcal.kg$^{-1}$, and a decline in mass yield of 85-71% at 10-60 min residence time was obtained for the sunflower. The process of torrefaction produced a biochar of reduced hemicellulose content, and more lignin and cellulosic content. This process leads to a brittle, grindable, and less reactive biochar with a break in biomass interlocking blocks.

Corncob and khat stem biomass's energy content was explored via torrefaction, and optimization was enhanced by Jifara Daba and Mekuria Hailegiorgis (2023). Investigation performed at 200, 250, and 300°C; 15, 30, and 45 min. The volatile matter content reduced from 77.7-64% for the Khet stem and from 76.9-67% for the corn cob. Khat stems burn and ignite better due to their higher volatile content. The ash content of raw corn cob increased from 3.24-10% and khat from 7.4-15% respectively, as Khat contains more inorganic compounds than corn cob. A moderate improvement of about 6% was observed in the fixed carbon content of the khat stem and corncob across the temperature range, with similar carbon contents of 43.43% (corncob)and 42.18% (khat stem). Predicted corncob has higher energy content than khat steam. Khat stem has a mass yield (68.85%), energy yield (98.5%) and HHV (24.95 MJ.kg$^{-1}$), while corncob has a mass yield of 56.80%, energy yield (94.9%) and HHV (23.37 MJ.kg$^{-1}$).

The role of torrefaction on biomass stalk on fuel yield and properties by Chen et al. (2015) at 220,250, and 280°C temperatures was investigated. As temperature progresses, bio-char mass yield declines while the bio-oil yield advances significantly. HHV value improved from 16.53 MJ.kg$^{-1}$ for dried cotton stalk (DCS) to 20.31 MJ.kg$^{-1}$ for torrefied cotton stalk (TCS)at 280°C. The volatile content dropped from 75.38 (TCS-220) to 56.23wt% (TCS-280) with higher ash and fixed carbon content at higher temperatures. Torrefaction temperature significantly improves the% carbon (C) content and reduces the oxygen (O) content. The biomass stalk has poor thermal stability, leading to the decomposition of a large proportion.

Almond Shell (AS) and Olive pomace (OP) were torrefied at conditions of 280-320°C, 500°C, and at various times by Alcazar-Ruiz et al. (2022).In their study, OP was confirmed to be thermally unstable compared to AS. OP has the highest carboxylic acid yield at (280°C; 20s) while AS at (300°C; 20s). As torrefaction became severe, the phenolic compound was noticeable for OP. This was attributed to the elevated lignin content and natural metals present in Olive Pomace that enhance catalytic reactions during the process. The maximum yield (47.7%) was achieved at (320; 240 s).

Bach et al. (2013) compared the role of process parameters on Norway spruce (softwood) and birch (hardwood) local biomass in a wet torrefaction process of 175,200, 225°C and at 10,30 and 60 min. The energy yield was observed to decline as temperature and holding time increased. Hence, it has a significant influence on fuel properties and solid products. However, the lower yield of solid products was observed at smaller particle sizes. The analysis and predictions proved that greater heating values are obtained at lower temperatures and shorter times. The fixed carbon content of truce wood biochar products was enhanced from 13.3-27.1% and 10.3-27.5% as the temperature and holding time advanced. Torrefied spruce experienced an HHV rise from 1.9-12.5% while torrefied birch had a 1.3–15.0% increase in the range of 175-225°C. At 225°C, the HHV of torrefied birch wood is comparable to that of torrefied spruce wood.

Norway spruce stem wood, stump, and bark were torrefied in a tubular reactor (Wang et al. 2017). The mass yield of all the torrefied samples declined as torrefaction conditions became severe which is from 225°C, 30min to 300°C, 60min. Stump recorded a drop in mass of 44% and 54% at 300°C for 30 and 60min, while stem wood showed a 30% and 40% decline in mass loss at 30 and 60 min residence time under 300°C residence time.

A carbon-rich solid feedstock was produced from torrefied olive mill waste (TPOMW) in a study by Benavente and Fullana (2015) carried out at 150-300°C for 2h. The study showed that carbon content was enhanced from 56-68 wt%%

and HHV from 26.4-30.0 MJ.kg$^{-1}$, by increasing the process temperature, which upgraded the value of the TPOMW comparable to sub-bituminous coal. Optimal heating value and minimised energy loss were obtained at 200°C. The synergetic process of torrefaction and densification was observed to enhance the energy density of TPOMW to a maximum of approximately 242% at t-TPOMW-300 briquettes.

Cetinkaya et al. (2024) also attempted to optimize the temperature and holding time as process parameters on Rosa Damascena Mill solid waste (RP) and red pine sawdust (PS). They produced bio-pellets of different weight ratios. The average HHV of the RP sample shifted from 19.8 MJ.kg$^{-1}$ for the raw PS sample to 21.2 MJ.kg$^{-1}$ at (290°C; 60 min). The average HHVs of the RP raw samples increased from 18.3 MJ.kg$^{-1}$ temperature to 21.3 MJ.kg$^{-1}$ at 290°C;60 min. It is also worth noting that the mass yields declined at severe torrefaction conditions ($p < 0.05$). At (290°C; 60 min) mass yield of the RP (57%) and PS (63%), which are the lowest yields, was recorded.

The torrefaction of pomaces and nutshells in a muffle furnace was investigated by Chiou et al. (2015). Apple pomace has lower thermal stability, hence it was torrefied at 200, 230, and 260°C, while nutshell was torrefied at 230, 260, and 290°C; all at 20, 40, and 60 min. All the samples have high energy yield at 230°C, but declined rapidly at 260°C. Apple pomace greatly declined by 42.3-14.9% while grape pomace decreased the least, ranging from 92.3-59.7% with a residence time of 20-60 min residence. However, energy yield was steady at 290°C, recording the highest value (71.4%) with grape pomace at 20 min and 62.6% at 60 min. This could be connected to grape pomace having a high mass yield at these temperatures.

Solid fuel from the torrefaction of passion fruit peel waste (PF) and pineapple fruit waste (PA) was obtained by da Silva et al. (2022). It was carried out at 200, 250, and 300°C and (15 and 60 min)using the macro-TGA with GC-TCD/FID analysis. From the figure, it was obvious that the torrefaction process enhanced HHV with the highest value of 22.97 MJ.kg$^{-1}$ and 20.78 MJ.kg$^{-1}$, fixed carbon content of 52.95 wt.% and 40.19 wt.% for PA and PF at (300°C;60 min), respectively. Solid yields of 56.21% for PA and 40.86% for PF at 300°C, 60 min were obtained. This is as presented in Fig. 5

Dhungana et al. (2011) compared non-lignocellulosic and lignocellulosic waste biomass in a torrefaction process. The non-lignocellulosic biomass was undigested sludge, chicken litter, digested sludge, and, while coffee husk, switchgrass, and wood pellet are the lignocellulosic biomass waste. The investigation was conducted within 250-280°C, and the residence time was 15-60 min. The energy density of the biomass was enhanced, and some of the biomass polymers decomposed, letting out oxygen through $CO_2$ and $H_2O$, and retaining some carbon in char. HHV increased from 19.18-24.20 MJ.kg$^{-1}$ for non-lignocellulose biomass at (280°C; 30 min). Similar values are obtainable with lignocellulosic biomass. Results confirm that HHV increases steadily with higher temperature, as well as the residence time and a further increase in the energy density of this biomass.

The fuel properties of Olive pruning (OP) and vineyard pruning(VP) were improved by Duman et al. (2020) via

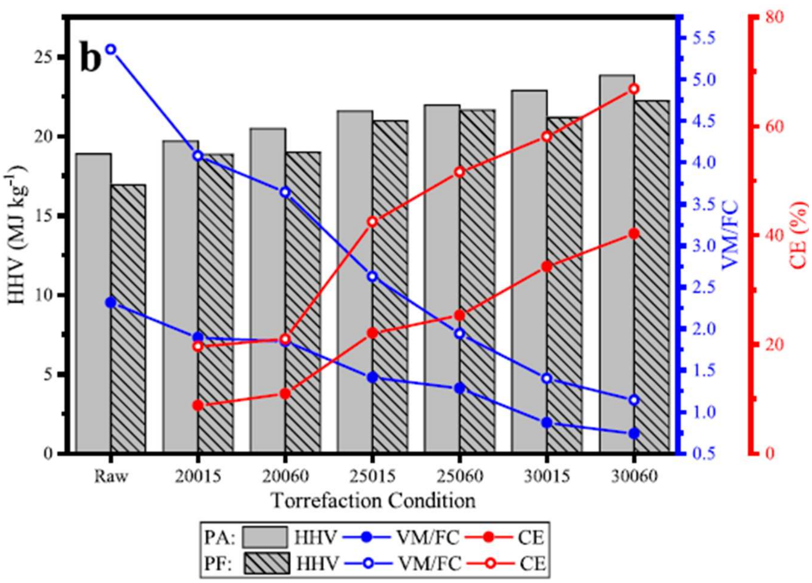


Fig. 5: Relationship between VM and FC (VM/FC), carbon enrichment (CE), and Higher heating value (HHV) (da Silva et al. 2022).

the torrefaction and hydrothermal route. Biochar has a mass yield of 82.1% (OP) and 81.0% (VP) at torrefying conditions (200°C; 60 min). Hydrochars have lower values of 58.2% for OP and 59.1% for VP. This difference in the mass yield can be attributed to the nature and amount of lignin in the biomass. In the HTC process, a lower mass yield was observed as the temperature increased, and a higher energy density of up to 1.45 times for hydrochar. Biochars have ignition temperatures at 270-346°C for OPB and 279- 353°C for VPB, and hydrochars between 268 and 409°C for OPH and 273 to 304°C for VPB. These temperatures exceed those of raw biomasses. However, the burnout temperature of biomasses was not affected by dry torrefaction, which is between 489 and 503°C for OP and approximately 490°C for VP, but the burnout temperature increased with HTC-treated biomass(from 494-561°C for OP and 487-534°C for VP). The ash content of biochar and hydrocarbon significantly differs and changes with biomass type.

The study investigating the combustion characteristics of torrefied almond hulls and shells, olive seeds, and corn stalks was conducted by Duranay et al. (2023). The torrefaction was carried out at 300±5ºC for 41 min. The torrefaction yield is dependent on the type of biomass. It was deduced that almond shells and olive kernels (hard woody waste) have higher solid product yields, which are 80.8% and 78.4%, respectively. Almond hull and corn stalks (flexible and fibrous waste) have lower solid product yields, which are 53.4% and 43.7% respectively. Harder agricultural wastes have a high amount of solid product based on their difficulty to thermally decompose, while more liquid and gaseous products were found during the thermal treatment of fibrous biomass. Torrefaction helps to improve the fixed carbon amount of almond and olive kernels by 30–55%. Volatile matter of corn stalk and almond hull declined by 42% and 32%, respectively, while the fixed carbon contents increased by 309% and 96%, respectively.

Cassava rhizome, sugarcane bagasse and straw briquette were torrefied at (250ºC; 90 min) by Granado et al. (2023). Cassava rhizome, sugarcane straw and sugar cane bagasse had relaxed densities of 1270 $kg.^{-3}$, 1240 $kg.m^3$ and 1300 $kg.m^{-3}$, respectively. Torrefied cassava rhizome, sugarcane bagasse and sugarcane straw gave improved HHV of 19.2, 18.4 and 19.0 $MJ.kg^{-1}$, respectively.

Auricularia auricula-judae, commonly known as the wood ear, was torrefied by Zhang et al. (2016b). Torrefaction was carried out under 200-320 °C and residence time (120-15 min). The mass yield continuously declined from 92.23% (200°C, 15min) to 46.65% (320°C, 120min) and the energy yield from 92.20% (200°C, 15 min) to 57.28% (320°C, 120 min). The C-content improved from 51.73% to 64.94% (320 °C;120min) and also an enhancement in the HHV from 21.13 $MJ.kg^{-1}$ -25.96 $MJ.kg^{-1}$ from 200°C; 15 min to 320°C; 15min. A decline was noticed in the O/C and H/C ratio from 0.571-0.332 and 1.594-0.907, respectively, within the torrefaction condition.

Leucaena, a woody biomass feedstock, was microwave torrefied by Huang et al. (2017). As the power level increases, the temperature and heating rate also increase. Microwave power, as an operating parameter, was noticed to have a greater effect than time. The HHV of the biochar increases with increases in power level and time. However, the reverse was witnessed with the energy and mass yield of the product as it declined from 72.30 wt.% at (100 W; 15 min) to 17.25% at 250W; 30min. A similar trend was observed for energy yield. HHV of 30 $MJ.kg^{-1}$ was reached at 250W power for 30 min processing time. The torrefied leucaena produced a fuel ratio of up to 3.7 at power levels of 200 and 250 W, which is greater than that of bituminous coal. As microwave power and time increased, the fixed carbon content rose while the volatile content decreased. This development suggests a potential alternative fuel source to substitute for coal or be used in co-firing.

In their 2017 study, Ianez-Rodriguez et al.(2017) optimized Greenhouse Crop Residue (GCR) torrefaction at various temperatures (200, 250, and 300°C) and times (15, 30, and 60 min). At 200°C, no significant impact on solid properties was observed. The most favorable conditions were noted at 263°C for 15 min. As the temperature increased to 300°C, the carbon content steadily rose from 34.02% to 43.78%, with a marked decrease in oxygen and a slight decline in hydrogen content. The resulting torrefied product had a high ash content (approximately 24%), making it more suitable for soil amendments than as a fuel source. Although the combination of 300°C and 15 min yielded the highest Higher Heating Value (HHV) of around 20.5, the low mass yield made it less desirable. Both mass yield and energy yield were inadequate at this temperature-time combination. The torrefaction process enhanced the sample's calorific value by increasing carbon content and reducing volatile matter. Hydrogen content remained nearly constant regardless of the torrefaction temperature.

The value of sugarcane bagasse (SBG) was upgraded for the production of quality fuel in a study by Jarunglumlert et al. (2022a). The torrefaction was both a dry and a wet process. The wet torrefaction process achieved a notable reduction in ash content, as it witnessed a less than 1% ash content above 180°C, making it a better fuel quality. The wet torrefaction process was also characterized by a higher yield than dry torrefied pellets. The heating value of both WT and DT ranged from 15.84-17.46 $MJ.kg^{-1}$; the raw baggase was 7.53 MJ.kg$^{-1}$ and the dry baggase was 15.04 MJ.kg$^{-1}$. Torrefaction was observed to enhance the calorific value by 5.0-17.9%. At high temperatures, the product heating values were enhanced, while mass yields were lower. Nevertheless, the specific energy demand of WTP production is almost double that of DTP.

Gaur & Pooniat (2024) improved the biochar quality of invasive weed (*Crotalaria burhia*) under the optimised condition of pyrolysis temperature:450°C, residence time of 1h. This process enhanced the carbon content of the waste biomass remarkably from 39.59-57.77% with a nose dive in hydrogen and oxygen content, resulting in a very low H/C and O/C ratio of 0.10 and 0.47, respectively. It also witnessed an astronomical increase in fixed carbon content from 19.09-81.24% and a major decline in volatile content from 70.26% to 8.48%. The process achieved a good biochar quality, which is suitable for enhancing soil fertility and carbon sequestration.

## ROLE OF CARRIER GASES ON THE QUALITY OF AGRO-WASTE-DERIVED SOLID FUEL

$N_2$, $CO_2$, and a gas mixture of air and $CO_2$ were used as carrier gases to torrefy corn cob under 250°C and 300°C for 1h (Lu & Chen 2013). All carrier gases showed solid product characteristics near to those of coal. Both carbon dioxide and nitrogen carriers exhibited similar FC, HHV, mass, and solid yield at 300°C. As shown in Fig. 6 (a), all the carriers exhibited solid yield above 50 wt.% gas at 250°C torrefaction. However, air+co2 carrier gas shows a solid yield of about 45.4 wt.% at 250°C. At 300°C, declined below 50wt% (by air + $CO_2$, $N_2$ and $CO_2$). The effect of the torrefaction temperature on the solid yield was observed to be more than that of the carrier gas. Fig. 6(b) shows that across all the carrier gas choices, the HHV (average) of corncob waste progresses from about 23.3 MJ.kg$^{-1}$ to -26.8 MJ.kg$^{-1}$, respectively, at 250°C and 300 °C; 1h as shown in Fig. 6 (c). These results confirm that $CO_2$ or air + $CO_2$ carrier gas can torrefy corncob waste. It was also observed that the kind of carrier gases also affects the amount of VM removal, and higher temperature with air+$CO_2$ taking the lead, however, with a subsequent reduction in FC generation.

Empty fruit bunches (EFB) were torrefied in a study by Uemura et al. (2017) under biomass combustion gas and nitrogen atmosphere at 473, 523, and 573 K. It was observed, as shown in Fig. 7, that the mass yield of torrefaction in the

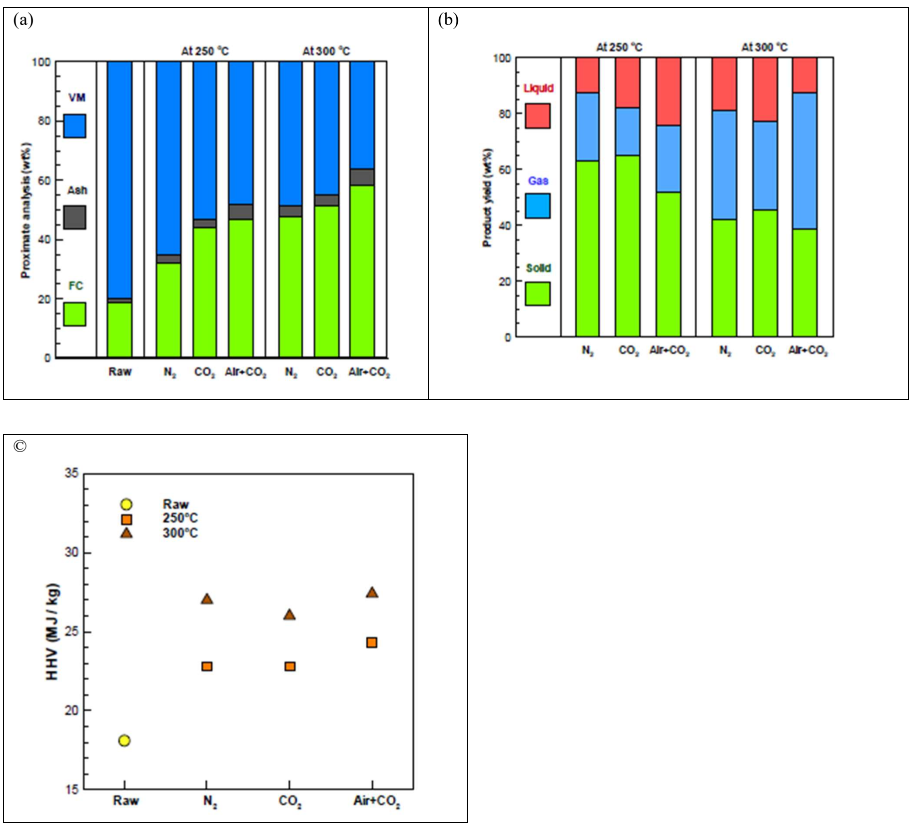


Fig. 6: (a)Proximate analyses of corncob waste, (b) Torrefaction product yields from corncob waste, (c) HHV profile of corncob waste (Lu and Chen, 2013).

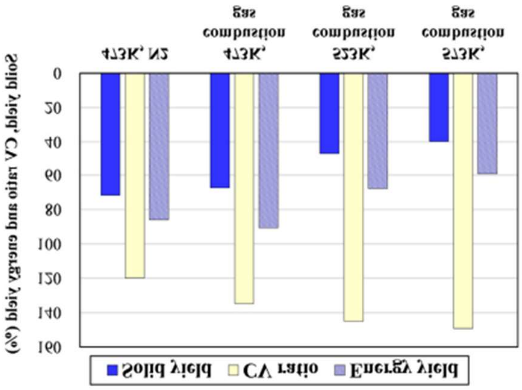


Fig. 7: Solid, calorific value and energy yields for torrefaction of EFB (Uemura et al. 2017).

nitrogen atmosphere is greater than that of combustion gas. $O_2$ and $CO_2$ decomposed more in the combustion gas. With a combustion gas atmosphere, the mass yield of torrefied EFB reduces with temperature increase. The torrefied EFB has a smaller mass yield of 67% in the combustion gas as temperature increases than that which was torrefied in N2 (72%), as $O_2$ and $CO_2$ enhanced decomposition in the combustion gas. This hence attests that combustion gas can help save energy.

Corncob was torrefied to charcoal by Li et al. (2018) under $N_2$ and $CO_2$ atmosphere at 200-300°C. Mass yields declined from 95.03-69.38% to 94.99-67.20% and increased HHV of 16.58-24.77 MJ.kg$^{-1}$ and 16.68-24.10 MJ.kg$^{-1}$ were obtained under $N_2$ and $CO_2$, respectively, within the torrefaction temperature. Hemicelluloses were not detected at a high temperature of 300°C. The C-concentration rises with increasing temperature from 200-300°C, while H and O concentrations decline. Corn cob torrefied at 260°C under $CO_2$ was observed as the most suitable condition. In the $N_2$ atmosphere, C-contents increased from 48.15-53.97%, accompanied by a decline in the H and O contents from 5.94-5.70% and from 45.91-40.33%, respectively. In the $CO_2$ atmosphere, the C-contents of the samples rose from 48.52-55.47%, while the H and O contents declined from 5.92-5.89% and 45.60-38.61%, respectively. The report clearly shows the greater role temperature plays than gas in the cellulose and hemicellulose decomposition.

Yard waste was valorised by Jaideep et al. (2021) to obtain solid fuel by torrefaction at 170, 200, 250, and 300°C; under different atmospheres of flue gas, $CO_2$ and $N_2$. As the temperature advances in the process, the mass yield declines. The highest mass yield was recorded in a flue gas atmosphere, while the lowest mass yield was with $N_2$. However, $CO_2$ carrier gas recorded the highest energy value (HHV) enhancement from 15.6- 22.2 MJ.kg$^{-1}$ at 300°C, and 98.1% energy yield. No visible property changes were reported for flue gas at 250°C. At 300°C, hemicellulose was completely degraded while cellulose was partially degraded. $N_2$ and $CO_2$ degrade the biomass much better than flue gas, as confirmed in other analyses. The energy yield using fuel gas is relatively constant across the temperatures, which defies the common trend, which is a lowering mass yield and energy yield with temperature increase. Despite the improvement in HHV, energy yield for $NO_2$ and $CO_2$ declined as temperature increased. The C content of 40.58%, H content of 5.08% and N content of 1.22 wt.%, N of EFB samples with 15.15 MJ.kg$^{-1}$ HHV were obtained. This shows that the combustion gas decomposes the EFB better than pure $N_2$.

Oil palm fiber pellets (OPFP) were torrefied in a study by Chen et al. (2016) under inert and oxidative atmospheres at(275-250)°C, $O_2$ concentration of 0-10 vol.% and duration of 30 min. The HHV of the biomass was enhanced significantly at 275°C in the oxidative environment, more than in the non-oxidative environment. However, at 300°C, regardless of the atmosphere, torrefied OPFP improved the fuel quality of the biomass. HHV of OPFP improved from 18.37- 20 MJ.kg$^{-1}$. At OPFP, torrefied in N2 attained HHV of 20.33 MJ.kg$^{-1}$. At 5% and 10% in the $O_2$ environment, the HHV of 22.22 and 22.59 MJ.kg$^{-1}$ was reached. It was therefore established that an inert environment supports the possibility of increasing the HHV of OPFP by temperature increase. However, in oxidative torrefaction, higher temperatures do not enhance the HHV.

Empty fruit bunches (EFB), mesocarp fiber (MF), and kernel shell(KS) were torrefied as a solid fuel (Uemura et al. 2011). High energy yield values of 96% and 100% were achieved for MF and KS, respectively, while EFB shows a poor yield of 56%.HHV increased from 17.02 MJ.kg$^{-1}$ to 20.41 MJ.kg$^{-1}$ in the process. Also, 19.61 MJ.kg$^{-1}$ for dried mesocarp fiber to 22.17 MJ.kg$^{-1}$ at 300°C. Similarly, the Kernel shell has HHV of 19.78 MJ.kg$^{-1}$ - 21.68 MJ.kg$^{-1}$ at 300°C torrefaction. The decrease in H2 and O2 as temperature rises due to dehydration and de-carbon dioxide from the biomass. The carbon content of the dried EFB moved from 45.53-49.56wt.%, and the H Content declined from 5.46-4.38 wt.%. The mesocarp fiber also has increased C-content from 46.93 to 48.68 wt.%, and an H content of 5.50 wt.% to 4.87%. The kernel shell C-content shifted from 45.87 wt.% to 54.21 wt.% while H content declined from 6.31-5.08 wt.%. A steady decline in mass yield as the temperature increases, with EFB as the highest decreasing ratio, and kernel shell has the lowest.

Pimchuai et al. (2010) torrefied some agricultural waste in $N_2$ at 250-300°C and 1-2 h. Maximum HHV of 25.68 MJ.kg$^{-1}$ was obtained at 300°C; 1.5 h for bagasse (comparable to HHV of lignite), least (21.02 MJ.kg$^{-1}$) at 250°C; 1 h. All the agricultural waste showed high HHV at 300°C;1.5h, rice husks (17.77 MJ.kg$^{-1}$), sawdust (23.94 MJ.kg$^{-1}$), peanut (19.1 MJ.kg$^{-1}$), water hyacinth (14.33 MJ.kg$^{-1}$). At severe torrefaction conditions, the moisture content and volatiles decreased. However, the fixed carbon content and ash content upwardly trend with higher temperature but decline massively as the residence time extends. No significant changes occur in volatile matters at 250°C, 1 h for all the residue. Mass and energy yields were reduced by about 41-78% and 55-98% of their initial values. The highest torrefaction temperature produces the lowest mass and energy yield.

The conditions of temperature and time in the torrefaction process were investigated on Norway spice stem wood, stump, and bark (Wang et al. 2017). The role of temperature was visible as the mass yield decreased across the temperature profile, which was significant and is associated with hemicellulose decomposition. At 300°C, stem wood lost was 30 and 42 wt%% with holding time of 30 and 60min, whereas the stump is 44 wt%.% and 54 wt%. A very slight reduction was witnessed with cellulose contents of the stem wood and the stump at 275°C. However, the cellulose content drastically reduced at 275 °C, with only a negligible remnant at 300°C torrefied biomass.

The effect of operating conditions on torrefied olive tree pruning was experimentally examined by Martín-Lara et al. (2017). At 300°C, 60 min, the fuel ratio shifted from 0.23-0.39, improving its fuel quality. O/C-1.02 (raw) reduced to 0.90 while H/C-0.17 (raw) to 0.15 at 300°C; 10 min. The decline in H/C attests to the moderate increase in the carbon content compared to other elements, and that of O/C is connected to the production of volatiles such as CO, $CO_2$, and $H_2O$. The elemental composition also confirms the shift of the native olive sample from that of lignocellulosic biomass to that of coal. The HHV of the biomass increased tangibly from 17.32 MJ.kg$^{-1}$ (native olive tree) to 20.50 MJ.kg$^{-1}$ at 200°C; 60 min torrefaction condition. However, the HHV drops at higher temperatures and longer residence times. The hemicellulose was strongly degraded in N2 atmosphere at high torrefaction conditions, and the thermal stability of cellulose was modified. The volatile content declined from 72.9% (200°C;10 min) to 69% (300°C; 60min), and the fixed carbon improved from 20.4% at 200°C; 10 min to 27.2% at 300°C; 60 min.

Martín-Pascual et al. (2020) numerically modelled olive tree waste biomass under torrefaction conditions of (200-300°C) and (0-120 min). Advancement in HHV of the torrefied sample was noticed within the 200-275°C range. However, the reverse was witnessed at 275-300°C, as the HHV declined. There were no remarkable differences in HHV with residence time at low temperatures, except for 120 min. It was generally inferred that the temperature shortens the time required to reach maximum HHV. It was then concluded that the optimum condition was 275°C, 30 min, with an optimum of 5830 cal.g$^{-1}$ HHV. A mass yield between 97.48-57.61% was achieved, which declines with the increasing residence time and temperature.

Oil palm agricultural residues, which are oil palm fronds (OPF)- non-woody biomass and *Leucaena leucocephala* (LL) -woody biomass, were also torrefied by Matali et al. (2016). The experiment was carried out within 200-300°C, and 60 min in an anoxic condition. At 300°C, $O_2$ and $H_2$ declined by 28% and 34% for torrefied OPF and LL, respectively, while C-content improved by about 37% for both torrefied samples. Fixed carbon was more than twice for all torrefied biomass, with OFP having the highest at 54 wt.%. $H_2$ and $O_2$ content with torrefaction was connected to the destruction of the (-OH) group in biomass samples, producing solid hydrophobic fuel. Mass yield experienced a 50% decline, with the raw biomass at 300°C for both OPL and LL. This was due to moisture removal and the release of volatiles such as hemicellulose and short-chain lignin compounds. Energy yield value reduced from 99.9 wt.% (OFP-200°C) to 71.2 (OFP-300°C); 29 wt.% and 40 wt.% for torrefied OPF and LL, respectively. HHV of torrefied OFP and LL at 300 °C; 60min improved from 18-25 MJ.kg$^{-1}$, for raw OFP and LL, comparable to sub-bituminous coal. Torrefied OPF was enhanced in energy densities by a factor of 1.42, while LL, respectively, by 1.39 at 300°C.

Wet torrefaction (WT) process was carried out on rice husk from 150-240°C for 60 min (Zhang et al. 2017). The mass yield decreased from 86.7-47.9% within the range of 150-240°C. Likewise, the energy yield during WT had a greater value than that of mass yield. Energy density was enhanced via torrefaction as it increased from 1.01 (150°C) to -1.12 (240°C). The HHV value was improved from 16.2 MJ.kg$^{-1}$ (RH) to 18.1 MJ.kg$^{-1}$ at 240°C and a C-content enhanced from 40.8% (RH) to 45.8% (240°C). The atomic ratio O/C of RH declined from 0.74-0.54, and H/C shifted from 1.68-1.36, which was due to the dehydration, decarboxylation, and demethanation reaction.

High-energy-yield biocoal was obtained by torrefaction of rice straw within 250-400°C and an isothermal time of 30 min in a nitrogen atmosphere by Pandey et al. (2019). The optimization of the process parameter brought about a desirable HHV of the torrefied product (bio-coal), which was equivalent to that of bituminous coal in thermal power plants. The energy yield decreases steadily from 75% at 250°C to 62% at 400°C with temperature increases. GCV of raw rice straw powder was enhanced from 3640 kcal.kg$^{-1}$ (untorrefied), 3762 kcal.kg$^{-1}$ (250°C), 4342 (300°C), 5129 kcal.kg$^{-1}$ (350°C) and 5339 kcal.kg$^{-1}$ (400°C).

At 200-250 °C, structural deformation and decoloration occur from light brown to dark brown. Above 300°C, a destructive drying phase where exothermic reaction and gas production (CO and other hydrocarbons) increase takes place, transforming the product from dark brown to black due to carbonization and devolatilization. As shown in Fig. 8 (a,b), the DTG peaks around 290-327°C, thermal degradation of hemicellulose and cellulose results in the release of volatile matter. At torrefaction 350°C and 400°C, the peak of hemicellulose and cellulose is almost extinct, an indication of total degradation of both hemicellulose and cellulose, while lignin is partially retained. The peak between 440-480°C denotes the lignin.

Coffee residue, sawdust, and rice husk were also torrefied to examine their solid fuel properties in a study carried out by Chen et al. (2012) at 240°C and 270°C, 0.5 and 1 h. The

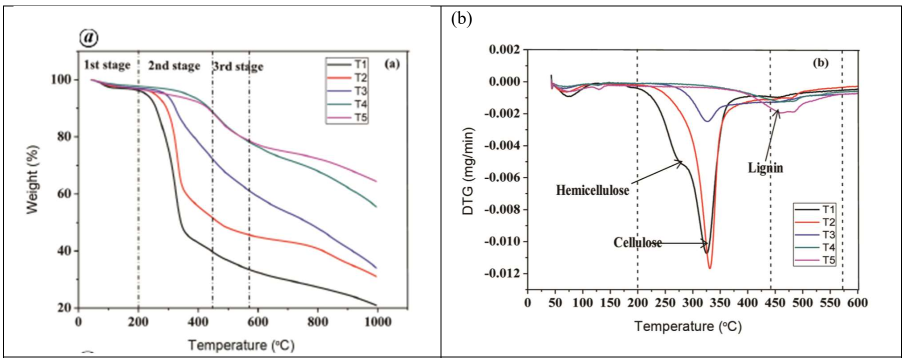


Fig. 8:(a) TGA and (b) DTG curve of raw rice straw and torrefied product. (Pandey et al. 2019).

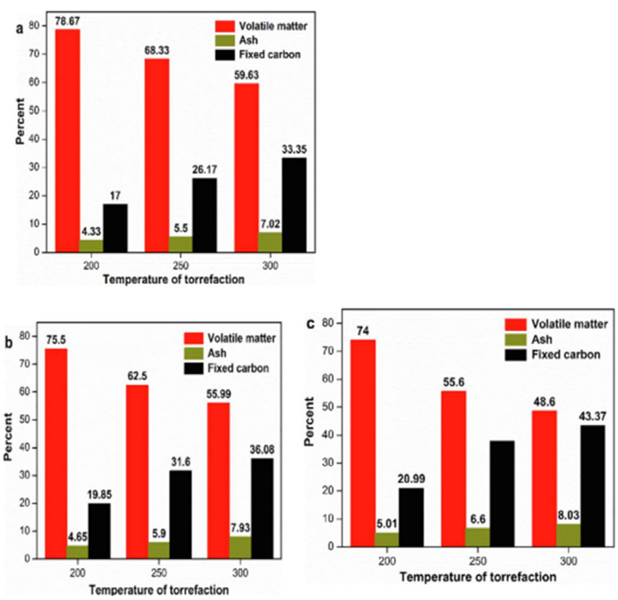


Fig. 9: Proximate analysis of torrefied MCR for: (a) 30 min; (b) 45 min; (c) 60 min RT at different torrefaction temperatures (Patidar & Vashishtha 2021).

result was compared with high-volatile bituminous and low-volatile coal. HHV of the coffee residue increased from 20.2 $MJ.kg^{-1}$ - 28 $MJ.kg^{-1}$ at 270°C, 60min. It was observed that coffee residue has more hemicellulose content, which makes it the most active biomass with improved HHV up to 38%. The properties of the torrefied biomasses were close to high-volatile coal at higher torrefied temperature and duration.

(Teh & Jamari 2016 torrefied rice husk and rice straw biomass at 220, 250, and 280 °C, 30 min and under the heating rate of 15 $°C.min^{-1}$. HHV of rice husk increased from 17.67 - 21.46 $MJ.kg^{-1}$ at 280°C. The HHV for rice straw was enhanced from 18.32 - 21.14 $MJ.kg^{-1}$ at the 280°C torrefied state. The energy yield of the torrefied rice husk was 93.47%,95.41% and 92.51% at 220,250 and 280°C. Rice straw has an average energy yield of 93.77%, 98.83% and 98.41% at 220, 250 and 280°C. An optimal temperature of 250°C gave the most valuable biofuel.

Mustard crop residue MCR was characterized and torrefied by Patidar & Vashishtha (2021) at 200, 250, 300°C and 30, 45, 60 min. The Highest mass yield was 95.54% at 200°C, 30 min; the lowest yield was 64.5% at 300°C,60 min. Also, the energy yield from 95.54% (200°C, 30min) to 65.23% (300°C, 60 min). The percentage of carbon also increases with the severity of torrefaction due to the release of volatiles. The HHV increases from 16.92 $MJ.kg^{-1}$ (MCR raw) - 21.94 $MJ.kg^{-1}$ for torrefied MCR (300; 60min). It experienced different stages of decolouration due to the thermo-degradation of the biopolymer and the oxidative reaction between the MCR and the atmosphere. As the temperature increased from 200-250°C, light volatiles were emitted, while hemicellulose and light aliphatic compounds were degraded. The effect of torrefaction conditions is presented in Fig. 9.

Sadaka and Negi (2009) enhanced the bioenergy properties of straws and wasted cotton gin feedstock by torrefaction at 260°C and varied time (0-60) minutes. In another phase of the experiment, wheat straw was torrefied at (200, 260, and 315 °C) and (60, 120, and 180 min). At 260°C, across all the residence time, there was no tangible decline in volatiles for wheat and rice straw. However, the HHV of wheat straw, rice straw, and cotton gin waste was enhanced by 15.3%, 16.9%, and 6.3% at 60 min. At 260°C, 60min, rice straw recorded the highest weight loss (30.7%) while cotton gin waste showed the lowest weight loss, due to its higher amount of lignin content than wheat and rice straw. Wheat straw showed a rise in HHV from 16.60- 22.75 $MJ.kg^{-1}$ at 315°C, 180 min. It was also obvious that the torrefied wheat biomass became very dark as the temperature and time advanced. It also experienced a decline in the mass yield at higher temperatures.

## THE ROLE OF PRESSURE ON THE QUALITY OF AGRO-WASTE-DERIVED SOLID FUEL

Rice straw was also torrefied by Seithtanabutara et al. (2023), in a bid to know the role of pressure in enhancing its fuel properties. An initial investigation was carried out under (- -0.4, 0.4, 0.8 and 2 bar), 200°C, and 40 min. Although torrefied products are dark compared with the raw material, the product from (- -0.4 bar) is slightly darker and more brittle compared to the torrefied product of 0.8 bar and the 2 bar, respectively. It was attributed to negative pressure causing easier wall explosion than positive pressure, promoting better decomposition of the biomass structure. Torrefaction at -0.4 bar has a lower mass yield than higher-pressure torrefaction. However, there were no noticeable differences in SEC for negative and medium positive pressure. At 0.8 and 2.0 bar pressures, 0.8 and 2.0 bar pressures have similar mass yields. Moreover, the 2.0 bar torrefied sample has higher HHV and, consequently, a higher EDR. Hence, torrefaction at 2 bar pressure produces the highest energy yield of 94.95% and EC (25.43 $Wh.g^{-1}$), high. At -0.4 bar, the lowest energy yield of 92.93% and the lowest energy consumption of 24.79 $Wh.g^{-1}$ were obtained. This indicates that the performances of EY and SEC are dependent on torrefaction pressure.

## INFLUENCE OF BULK ARRANGEMENTON THE PERFORMANCE OF TORREFIED AGRICULTURAL WASTE BIOMASS

Soponpongpipat & Sae-Ueng (2015) confirmed that biomass bulk arrangement affects the decomposition pathway of sugarcane trash in a torrefaction. The experiment was performed within a temperature range of 250-290°C and for 60 min. Untreated biomass has an HHV of 16.08 ± 0.23 $MJ.kg^{-1}$. However, as the temperature progresses, the HHV rises from 18.55 - 20.76 $MJ.kg^{-1}$ to 250-290°C in the hollow bulk arrangement. In the dense bulk configuration, the Higher Heating Value (HHV) of the torrefied biomass ranged from 20.18 to 23.87 $MJ.kg^{-1}$ as the temperature increased from 250 to 290°C. Comparatively, the dense bulk arrangement yielded higher HHV values than the hollow bulk setup across all temperature ranges. The dense bulk arrangement facilitates an autocatalytic decomposition pathway, leading to more extensive decomposition. In the hollow bulk configuration at 250°C, the rate of weight loss (Mt/Mo) decreased rapidly with increasing time until 400 seconds. Conversely, in the dense bulk density setup, weight loss declined quickly until reaching 700 seconds, after which it stabilized at a constant level.

The impact of the dry and wet torrefaction process with an additive was compared on the pyrolysis performance of

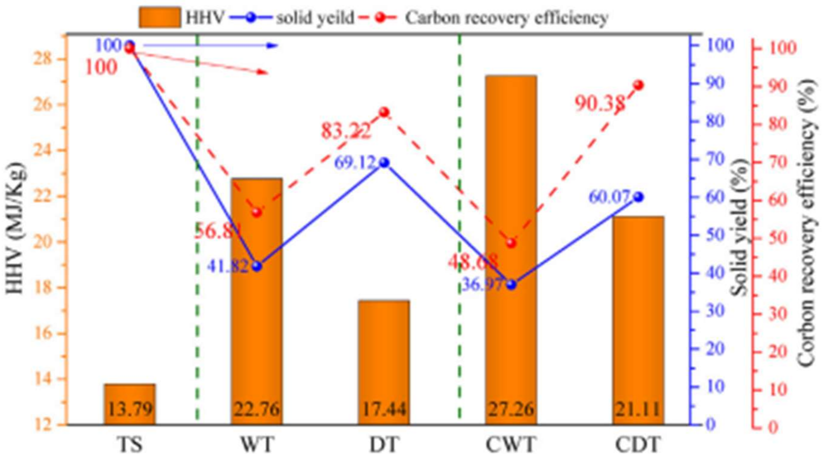


Fig. 10: HHV, solid yield and CRE of torrefied biochar (Sun et al. 2019).

tobacco stalk Sun et al. (2019). In this study, HHV improved after the wet/dry torrefaction process, with WT having 22.76 $MJ.kg^{-1}$ HHV and DT having 17.44 $MJ.kg^{-1}$. It was also observed that additives enhanced HHV from 13.79-27.26 $MJ.kg^{-1}$.

As shown in Fig. 10, DT and CDT have a much higher solid product of 69.17% and 64.19% respectively, compared to wet torrefaction (WT)-41.78% and catalytic wet torrefaction (CWT)-36.48%. It was also observed that both dry and wet torrefaction decreased the H/C and O/C of the product, with the torrefied sample's aromaticity in the coal range. However, CWT showed a more significant decrease in H/C and O/C from 1.89-0.24 and 1.89-0.55, respectively. WT has more heat, mass transfer and contact area than DT.

In addition, catalytic torrefaction(wet/dry) produces a lower yield than non-catalytic, converting TS into bio-oil and non-condensable gases during torrefaction. There is a significant decline in the hemicellulosic content for both processes. However, it was converted to gas and liquid products after CWT or CDT. Hence, WT with additives effectively improved the energy value of torrefied biochar.

The torrefied lemongrass (Cymbopogon citrates) residue was examined by Tan et al. (2017) using microwave-induced torrefaction at 200 -300 $^{o}$C in an anoxic atmosphere. This process helps to improve the HHV of raw biomass, which was 17.93 $MJ.kg^{-1}$ - 19.37 $MJ.kg^{-1}$ at 300 $^{o}$C, with a 37.7% increase in fixed carbon of lemongrass residue. From raw lemon grass residue to (300 $^{o}$C;30 min) H/C moves from 0.28-0.24, a 14.3% increase and O/C 0.80-0.32, a 60.0% increase, respectively, were observed. Also, the mass and energy yield of the torrefied lemongrass residue declined from 81.50%-61.20 and 83.85 to 66.11% respectively. The physical appearance of the untreated lemon grass visibly changed from medium brown to dark brown at 300°C. The decoluration due to exothermic reaction in this process led to the loss of moisture content, $CO_2$, large amounts of acetic acid and phenols. The C-content improved slightly from 47.18 wt.% (untreated) to 49.05% at 300°C,30min. However, the H content declined moderately from 13.12 wt%-11.95 wt% at 300°C,30min. Moreover, the O content massively declined from 37.93wt% to 15.63 wt%. Table 1 shows the calorific/energy value of common agricultural residues.

## RELEVANT ADVANCES ON THE TECHNO-ECONOMIC IMPLICATION OF AGRO-WASTE TORREFACTION

### Integrated Torrefaction, Scaling Up and Pelleting Process Approach for Economic Feasibility and Environmental Impact

The constraint on torrefaction of biomass and its preference over coal is its cost implication. However, the larger plant capacities with an integration system will serve to cut down cost, and achieving carbon credits can improve economic viability (Niu et al. 2019). This will help to reduce costs and improve market penetration (Kumar et al. 2017).

The torrefaction process also helps achieve a reduction in carbon emissions when carbon capture and utilization processes are incorporated into the facility. Instances are presented by Cutillo et al. (2024) on the integration of torrefaction with chemical looping combustion and methanation to achieve net-zero or negative carbon emissions. According to Pirraglia et al. (2013), carbon credit serves as a route to increase income on the internal rate of return (IRR) and net present value (NPV) per metric ton of a torrefied biomass. Batidzirai et al. (2013) also attested that technological scaling up can help achieve a 50% reduction in total cost and cut down production costs.

Table 1: Calorific/Energy value of Common Agricultural Residues.

| References | Process conditions | Calorific value | Common agricultural waste residue/ feedstock | Mass Yield (M.Y)/ Energy yield (E.Y) |
|---|---|---|---|---|
| (Abdullah et al. 2022) | 230-300)°C;<br>(30-90)min;Muffle Furnance under $N_2$;<br>Dry torrefaction | (22-25) $MJ.kg^{-1}$<br>27 $MJ.kg^{-1}$-300 C | Walnut shell (WS) 30%:<br>Pearl Millet (PM) 70% | M.Y: 41-91% |
| (Yang et al. 2015) | (180-260)°C;<br>stainless steel batch reactor;<br>Wet torrefaction | 17.5-25.3 $MJ.kg^{-1}$<br>17.7-25.7 $MJ.kg^{-1}$<br>18.4-23.6 $MJ.kg^{-1}$ | Humulus Lupulus (HL)<br>Plumena Alba (PA)<br>Calophyllum Inophyllum (CIL) | M.Y: 26.5% (HL)<br>M.Y: 31.5% (PA)<br>M.Y; 50.9% (CIL) |
| (Yue et al. 2017) | (250-300)°C;<br>steel batch torrefaction reactor, electric furnace; Wet torrefaction | 17.33-23.62 $MJ.kg^{-1}$<br>16.45-26.88 $MJ.kg^{-1}$ | Energy sorghum (ES)<br>Sweet sorghum baggase(SSB) | M.Y: 43-65% (SSB)<br>M.Y: 51-70% (ES) |
| (Zhang et al. 2016a) | (130-220)°C; autoclave reactor; Wet torrefaction | 14.34-19.84 $MJ.kg^{-1}$ | Duckweed | M.Y:30.4-64.8%<br>E.Y: 40.1-77.9% |
| (Akhtar et al. 2021) | (200-320)°C<br>10-60min; Tube furnace, $N_2$, Dry torrefaction | 3600-5444 $kcal.kg^{-1}$<br>(290 °C; 20 min)<br>3696-4481 $kcal.kg^{-1}$<br>(270°C;30 min)<br>(3435-4370) $kcal.kg^{-1}$<br>(260°C, 60 min) | Corncob (CC)<br>cotton ball (CB)<br>sunflower (SF) | M.Y: 45-54% (CC)<br>M.Y; 71-84% (SF)<br>M.Y; 44-88% (CB) |
| (Jifara Daba & Mekuria Hailegiorgis 2023) | (200-300)°C;<br>15-45 min; Muffle furnace<br>$CO_2$ gas; Dry torrefaction | 14.80-23.37 $MJ.kg^{-1}$<br>16.54-24.95 $MJ.kg^{-1}$, | Khat stem<br>Corncob | E.Y-98.5% (CC)<br>E.Y-94.9% (KS) |
| (Chen et al. 2015) | (220-280)°C; Tubular furnace, $N_2$ flow | 16.53 -20.31 $MJ.kg^{-1}$ | Cotton stalk | ------------- |
| (Alcazar-Ruiz et al. 2022) | (280-320)°C, 500°C | 22.56-<br>17.93- | Olive pomace (OP)<br>Almond shell (AS) | ------------- |
| (Bach et al. 2013) | (175-225)°C;<br>10-60min; 15.54-250 bar;<br>Wet torrefaction; Benchtop autoclave reactor | 19.94-~20.42 $MJ.kg^{-1}$ | Norway spruce (softwood)<br>Birch (hardwood) | S.Y: 76.4-731.1(15.54-250 bar)<br>S.Y:88.3-69.7(175-225 degC/spruce)<br>S.Y:79.0-58.0(175-225 degC/spruce) |
| (Benavente & Fullana 2015) | (150-300) °C; 2h;<br>oven model UFP500 from Memmert GmbH | 26.4-30.0 $MJ.kg^{-1}$ | Torrefied olive mill waste (TPOMW) | S.Y: 35-98% |
| (Cetinkaya et al. 2024) | (250-290)°C;<br>15-60min;<br>Ash furnace (Nüve MF 5000). | 19.8-21.2 $MJ.kg^{-1}$<br>(290°C;60 min).<br>18.3 $MJ.kg^{-1}$ -21.3 $MJ.kg^{-1}$<br>(290 °C;60 min) | Rosa Damascena Mill solid waste (RP)<br>Red pine sawdust (PS). | M.Y: 89-57% (RP)<br>M.Y; 90-63% (PS) |
| (Chiou et al. 2015) | (200, 230, and 260)°C;<br>230, 260, and 290 °C<br>An Isotemp muffle furnace under $N_2$ | | Apple (A) grape pomace (G), olive and tomato pomace (T) | - |
| (da Silva et al. 2022) | (200, 250, and 300°C);<br>(15 and 60 min) | 18.83-20.78 $MJ.kg^{-1}$<br>20.48-22.97 $MJ.kg^{-1}$ | Passion fruit peel waste (PF)<br>Pine-apple fruit waste (PA) | S.Y:77-81% (PF/200C);41-44% (300C)<br>S.Y: 56-61% (PA/300C); 87-90%(200C) |
| (Dhungana et al. 2011) | 250-280°C; 15-60 min<br>Muffle furnace | 19.18-24.20 $MJ.kg^{-1}$<br>19.89 $MJ.kg^{-1}$<br>20.16 $MJ.kg^{-1}$ | non-lignocellulose biomass<br>switch grass<br>coffee husk | 86.35- 96.60% (250C);62.80-89.85% (280C)<br>74.84-94.53% (250C); 56.84-88.88% (280C)<br>86.06-98.68% (250C);73.71-97.73% (280C) |
| (Duman et al. 2020) | 200-350°C;120min<br>500 mL batch reactor. | 23.4-26.5 $MJ.kg^{-1}$<br>20.9-28.4 $MJ.kg^{-1}$ | Olive pruning (OP)<br>Vineyards pruning(VP) | HY;42-60% (VP);<br>42-58% (OP) |

Table Cont....

| References | Process conditions | Calorific value | Common agricultural waste residue/ feedstock | Mass Yield (M.Y)/ Energy yield (E.Y) |
|---|---|---|---|---|
| (Duranay et al. 2023) | 300°C+/-5C; 41min; cylindrical tube furnace | --------------- | almond hulls<br>Almond shells,<br>Olive seeds<br>corn stalks | M.Y; 53.4% (AH)<br>M.Y; 80.8% (AS)<br>M.Y: 78.4% (OS)<br>M.Y: 43.7% (CS) |
| (Granado et al. 2023) | (250ºC; 90 min) | 17.8-19.2 $MJ.kg^{-1}$<br>16.8-18.4 $MJ.kg^{-1}$<br>16.9-19.0 $MJ.kg^{-1}$ | Cassava rhizome,<br>sugarcane bagasse<br>sugar cane straw | 77.7% (CR)<br>62.5% (SB)<br>58.0% (SC) |
| (Zhang et al. 2016a) | 200-320°C; (15-120 min) | 21.13 $MJ.kg^{-1}$ -25.96 $MJ.kg^{-1}$ | Auricularia auricula-judae (wood ear) | ------------------ |
| (Huang et al. 2017) | (100 W; 250W) (15-30min);single-mode microwave oven | 21.18-29.65 $MJ.kg^{-1}$ | Leucaena, woody biomass | M.Y: 17.27-72.3%<br>E.Y: 27.87-83.0% |
| (Ianez-Rodriguez et al. 2017) | (200, 250 & 300°C) (15-60 min). | 17.75- 20.5 $MJ.kg^{-1}$ | Greenhouse Crop Residue (GCR) | |
| (Jarunglumlert et al. 2022a) | 240-300°C | 15.84-17.46 $MJ.kg^{-1}$ | sugarcane bagasse (SBG) | --------------------- |
| (Lin et al. 2021) | (210- 300°C);<br>(30 and 60 min;<br>A steel batch torrefaction reactor | 19.9 $MJ.kg^{-1}$-27.7 $MJ.kg^{-1}$;<br>19.1 $MJ.kg^{-1}$-23.3 $MJ.kg^{-1}$ | Ananas comosus peel (ACP)<br>Annona squamosa peel (ASP) | 48-73.3%<br>48-87.3% |
| (Lu and Chen, 2013) | 250°C; 60 min<br>300°C; 60 min;<br>An electric furnace. | 22.8-24.3 $MJ.kg^{-1}$<br>27.0-27.4 $MJ.kg^{-1}$ | Corncob | >50% (250C)<br><50% (300C) |
| (Uemura et al. 2017) | 473, 523 and 573 K, $N_2$,<br>vertical tubular reactor | 22.6 $MJ.kg^{-1}$ | Empty fruit bunches (EFB) | E.Y: 91% (473k)<br>S.Y: ~70% (473k) |
| (Li et al. 2018) | 200-300°C;<br>Horizontal tubular quartz tube reactor heated by a furnace | 16.58–24.77 $MJ.kg^{-1}$-N2 atm<br>16.68–24.10 $MJ.kg^{-1}$CO2 atm | Corncob | M.Y: 69.36-95% (N2)<br>M.Y: 67.2-95% (C02) |
| (Jaideep et al. 2021) | 170, 200, 250, and 300°C | 15.6- 22.2 $MJ.kg^{-1}$ | Yard waste | M.Y: 60-87.6%;<br>E.Y:81-95% (N2)<br>M.Y: 61-91%;E.Y: 98-103% (CO2)<br>M.Y: 73-89% ; 86.2-86.7%(flue gas) |
| (Chen et al. 2016) | (275-250)°C | 18.37-20 $MJ.kg^{-1}$-N2<br>22.22-22.59 $MJ.kg^{-1}$-O2 | Oil palm fiber pellets (OPFP | S.Y:43 -65 wt.% |
| (Uemura et al. 2011) | 300°C;<br>Horizontal<br>tubular type reactor | 17.02-20.41 $MJ.kg^{-1}$.<br>19.61- 22.17 $MJ.kg^{-1}$.<br>19.78 - 21.68 $MJ.kg^{-1}$ | Empty fruit brunch (EFB)<br>Mesocarp fiber (MF)<br>Kernel fiber | M.Y:24.16-43.16% (EFB)<br>M.Y: 52.46-63.08% (MF)<br>M.Y: 71.27-77.44% (KF) |
| (Pimchuai et al. 2010) | 250-300°C and 1-2 h;<br>Muffle furnace, $N_2$ | 21.02-25.68 $MJ.kg^{-1}$<br>15.89-17.81 $MJ.kg^{-1}$<br>19.55-25.09 $MJ.kg^{-1}$<br>16.35-19.36 $MJ.kg^{-1}$<br>12.68-14.33 $MJ.kg^{-1}$ | Baggase<br>Rice husk<br>Saw dust<br>Pea nut<br>Water hyacinth | M.Y: 41-78%<br>E.Y; 55-98% |
| (Wang et al. 2017) | 275°C and 300°C;<br>bench-scale tubular reactor. | | stem wood, stump<br>bark woody biomass | M.Y: 60-90% (SW)<br>M.Y; 46-90% (S)<br>M.Y: 56-90%(W) |
| (Martín-Lara et al. 2017) | 200-300°C;<br>Electric muffle furnace | 20.09-20.50 $MJ.kg^{-1}$ | torrefied olive tree | M.Y: 57.0-87.4%<br>E.Y: 64.0-101.5% |
| (Martín-Pascual et al. 2020) | (200-300°C); (0-120 min);<br>Thermogravimetric analyser; $N_2$ | 4884-5893 $Cal.g^{-1}$ HHV | olive tree waste | M.Y: 57.61-97.48% |

Table Cont....

| References | Process conditions | Calorific value | Common agricultural waste residue/ feedstock | Mass Yield (M.Y)/ Energy yield (E.Y) |
|---|---|---|---|---|
| (Matali et al. 2016) | 200-300°C; 60 min; Horizontal furnace with 80mm-IDquartztube reactor, | 18.58 -25.16 $MJ.kg^{-1}$ 18.31-24.92 $MJ.kg^{-1}$ | oil palm frond (OPF), *Leucaena leucocephala* (LL) -woody biomass | M.Y: 43-92% ; E.Y: 60.1-93.9% (LL) M.Y:50-95%; E.Y:71.2-99.9% (OPF) |
| (Nam and Capareda, 2015) | (210, 250 and 290°C) (20, 40, and 60 min) bench-scale batch type Parr pressure reactor; $N_2$ | 20.3-28.6 $MJ.kg^{-1}$ 19.3-23.3 $MJ.kg^{-1}$ | Rice straw (RS) cotton stalk (CS) | M.Y:76.61-91.3% (RS) M.Y: 68.45-99.4% (CS) |
| (Zhang et al. 2017) | 150-240°C; 60 min; high-pressure batch reactor, Wet torrefaction, $N_2$ | 18.8- -18.4 $MJ.kg^{-1}$ | rice husk (RH) | M.Y: 27.4-42.7% (RH) |
| (Pandey et al. 2019) | (250-400)°C ; 30 min; Stainless steel (SS) Reactor; $N_2$ | 3762 -5370 $kcal.kg^{-1}$ | Rice straw (RS) | M.Y: 42.01- 72.6% (RS) E.Y; 62- 75% |
| (Chen et al. 2012) | (240 and 270°C); (30 and 60min), Reactor; $N_2$ | 20.2 -28 $MJ.kg^{-1}$ 17.8- 18.4 $MJ.kg^{-1}$ 16.2-18.2 $MJ.kg^{-1}$ | Coffee residue, rice husk sawdust | E.Y: 88-99% |
| (Teh and Jamari, 2016) | (220, 250 and 280°C) ;30 min, Tubular reactor; $N_2$ | 18.44 -21.46 $MJ.kg^{-1}$ 18.78-21.14 $MJ.kg^{-1}$ | Rice husk Rice straw | M.Y:78.98-91.2%;E.Y: 92.51-95.41% (RH) M.Y: 82.28-89.85%; E.Y: 93.77-98.83% (RS) |
| (Patidar & Vashishtha 2021) | (200, 250 and 300)°C ; 30, 45, 60 min; Tube Furnace; $N_2$ | 16.92- 21.94 $MJ.kg^{-1}$ | Mustard crop residue MCR | M.Y; 53.47-95.54%; E.Y: 65.23-97.7% |
| (Sadaka & Negi 2009) | (260)°C; 0, 15, 30, 45, and 60 min (200, 260, and 315°C) (60, 120, and 180 min); Bench scale reactor; $N_2$ | 16.2-18 $MJ.kg^{-1}$ 14-15.6 $MJ.kg^{-1}$ 16 $MJ.kg^{-1}$ 16.60- 22.75 $MJ.kg^{-1}$ | Wheat straw, Rice straw Cotton gin waste Wheat straws | ------------------ |
| (Seithtanabutara et al. 2023) | positive and negative pressure (0.4, 0.8 and 2); bar) at temperature and time of 200-220°C and 30-50 min; stainless-steel tube reactor; $N_2$ | 17.29 $MJ.kg^{-1}$ (-0.4bar) 17.64 $MJ.kg^{-1}$ (2.0bar) | Rice straw | E.Y: 94.95% max. (2 bar); 92.93% min (0.4 bar) |
| (Soponpongpipat and Sae-Ueng, 2015) | 250, 270, and 290°C;60 min; stainless steel cylinder reactor; $N_2$ | 18.55 - 20.76 $MJ.kg^{-1}$ 20.18- 23.87 $MJ.kg^{-1}$ | sugarcane trash- hollow bulk arrangement compact bulk arrangement | --------------------------- |
| (Sun et al. 2019) | 240°C,1hr-DT/WT; $N_2$ With additive Fixed bed reactor with the quart tube | 22.76 $MJ.kg^{-1}$ -WT 17.44 $MJ.kg^{-1}$-DT 27.26 $MJ.kg^{-1}$-(WT+additive) 21.11 $MJ.kg^{-1}$-(DT+additive) | Tobacco stalk | WT:41.2% (S.Y) DT:69.12% (S.Y) CWT:36.97% (S.Y) DWT:60.07% (S.Y) |
| (Tan et al. 2017) | 200 -300°C; modified bench top microwave oven; $N_2$ | 17.93 - 19.37 $MJ.kg^{-1}$ | lemongrass (Cymbopogon citrates) residue | M.Y: 61.20- 81.50% |

A study by Zhao et al. (2024) reveals that the energy efficiency of torrefaction can be improved by its integration with steam gasification up to 58.9% which is higher than the direct gasification. Biomass is made an efficient fuel source by torrefaction, with its enhanced energy density and combustion characteristics.

Goyal et al. (2023) proposed an integrated system of torrefaction and pelleting process for rice straw. It synergizes torrefaction and pelleting steps into a single process, also harnessing the inherent natural lignin in biomass as a binder without the need for external binders and reducing process complexity. The economic analysis of this process revealed a return on investment (ROI) of 30%, a payout time of 2.4 years, and a break-even point of 42% at a selling price of $73 per ton of briquettes, indicating significant profitability potential.

Bampenrat et al. (2023) upgraded waste sugarcane bagasse (SBG) and palm kernel shell(PKS) through torrefaction, under a temperature of (225–300 °C) and residence time of (30–90 min). Torrefaction temperature has a stronger implication on mass yield and calorific value than residence time. The optimal conditions of SBG and PKS were attained at 275 °C for 90 min, having bio-coal values (approximately 23 $MJ.kg^{-1}$) and energy yields of 73.93-77.41%. This makes it fit to be co-fired with coal in thermal power plants. The energy yield and calorific value prove its economic viability.

Shah et al. (2012) In a bid to assess the techno-economic feasibility of a production-scale torrefaction, analysed its mass-energy balance was analyzed. In this study, the net external energy required for the torrefaction process increased while the energy efficiency decreased with increasing moisture content. However, both energy metrics show a decreasing trend as process temperatures increase. The unit torrefaction process cost decreases with decreasing initial moisture contents and decreasing torrefaction process temperatures. For the typical moisture content of 30% wet basis (wb), process temperature of 240°C, plant operating window of 6 mo $yr^{-1}$ and initial capital investment of $7.5 million for the system with rated capacity of 25 Tton. hr–1, the unit torrefaction process cost was estimated to be 17.5 $-$Tton^{-1}$. Additional system improvements through capital cost reduction and wider operating windows can yield a torrefaction product cost of ~12 $-$Tton^{-1}$.

Jarunglumlert et al. (2022b) measured the impact of the torrefaction process on the ash content and overall quality of the pellets from sugar cane bagasse. Wet torrefaction was found to significantly reduce ash content to 1% at temperatures above 180°C, resulting in higher quality and more marketable fuel pellets compared to dry torrefaction. An economic feasibility analysis revealed that the production of wet torrefied fuel pellets yields greater net present value and profitability than dry torrefied pellets, indicating that both methods are economically viable for producing biomass fuel pellets, with wet torrefaction being the more advantageous option.

A study by Abelha (2019) carried out a preliminary economic analysis on high moisture content roadside grass and low moisture content (wheat straw and miscanthus). The analysis indicated that all tested materials could be technically upgraded to commodity fuels. The analysis revealed that the upgraded roadside grass could be offered at an attractive price of 4.7 E/GJ, leading to an internal rate of return (IRR) of 14%, which could increase to 18% with reduced sludge disposal costs. In contrast, upgrading wheat straw was found to be unprofitable unless a gate fee could be charged, with a competitive price of 6.2 E/GJ yielding an IRR of 7%.

Alherbawi et al. (2024) examined the economic implications of pyrolyzing cucumber, tomato, and carrot wastes as feedstocks in various blends and conditions (temperature and moisture content. It carries out other investigations, such as product yields and energy requirements. The bio-oil yields were observed to increase with higher temperatures and moisture content, while biochar yields declined, and syngas production occurred only at elevated temperatures. Economic analysis revealed a promising return on investment (ROI) of 29% for the single component at 5% moisture content and 300°C, with a payback period of 3.4 years.

The techno-economic and environmental feasibility of rice husks was assessed by Diemuodeke et al. (2021) as a fuel source for a combined heat and power plant in a cluster of rice mills in Abakaliki, Nigeria.

The application of organic Rankine cycle-based synergy for heat and power plants was able to sustainably meet the energy demand of the cluster's rice mills. The analysis shows the capacity of rice husk to generate daily electrical power of 20-30 MWh and thermal power of 4-91 MWh with an efficiency of 14.5-21%. The proposed energy system offers a significant cost advantage, with electricity production costs ranging from 0.12 to 0.159 /kWh, compared to 0.947/kWh for diesel generators, while also contributing to substantial $CO_2$ emissions reductions of 270-483 $kg.MWh^{-1}$, thereby supporting Nigeria's commitments to the Paris Agreement.

Sarker et al. (2023) harnessed the torrefaction and pelletization process route for pellet production, providing a conceptual design for torrefied fuel pellet production. This is an attempt to reduce over-reliance on wood or fossil fuel for the target application in the rural areas. The entire design contains a torrefaction unit, grinding, preparation of pellet formulation, pelletizing, and finally cooling of pellets. It compares the process of pelletisation with (category 1) or without additives (category 2). The lowest selling price of generated torrefied pellets was found to be $103.4 and $105.1 per tonne at the plant gate for the categories, respectively. Sensitivity analysis shows that, among all variable costs, labor cost has the strongest influence on both net present value (NPV) and minimum selling price (MSP) in making pellets for both scenarios. Furthermore, the internal rate of return was found to be 25% and 22% at a 10% discounted cash flow rate for scenarios 1 and 2, respectively. The framework that was created was found to lessen over-dependence on wood or fossil fuels and facilitate the promotion of bioenergy in rural areas.

Winjobi et al. (2016) compared a one-step pyrolysis process with a two-step process that includes a torrefaction step. The economic analysis reveals that incorporating a torrefaction step reduces the minimum selling price of bio-oil, with the lowest price of 1.04 per gallon achieved at a torrefaction temperature of 330°C compared to 1.32 per gallon for the one-step process. However, there is a trade-off between the bio-oil quality and selling price, as a higher minimum selling price of 22.19 per GJ compared to 16.89 per GJ for the one-step process on an energy basis.

## FUTURE DIRECTION

The abundance of agricultural waste in certain regions of the world has created market opportunities for investors and scientists to transition into alternative sources of energy, of renewable and sustainable sources. Future Market Insight (Outlook 2022), projects that the production of biomass pellets from agricultural residue will increase by 7.1% between 2022 and 2032. Hence, creating an avenue to achieve a carbon neutral, reduce greenhouse gas (GHG) emissions, and abate pressure on the increasing demand for woody biomass as bioenergy sources.

The holistic implementation and adoption of torrefied biomass residue and pellets for energy (heat and electricity) production over coal power generation may be a long-term projection. However, the torrefaction and valorisation of agro-waste can be appreciated progressively by co-firing it with coal at various percentages of the torrefied agro-waste. Co-firing with a certain percentage of torrefied pellets has been seen to bring a significant reduction in greenhouse gas emissions (GHG).

Also, countries with a sufficient supply of agro-waste should promote its use as a domestic and industrial raw material, and can be used as exported to nations with a shortfall. The technology of torrefaction and pelletisation should also be encouraged for efficient transportation and storage means of agro-wastes.

## CONCLUSIONS

In pursuit of GHG net-zero emissions and to tackle the climate change crisis, energy decarbonization has become a global discourse. Several considerations and attempts to migrate or mitigate the overdependence on fossil fuels to renewable energy have been made across several technological frontiers. It is therefore concluded in this review that torrefied biomass provides a possibility to serve as a coal alternative if harnessed through sustainable routes such as torrefaction, as it also generates carbon-neutral energy. Torrefied biomass can be used directly or as a coal admixture for energy applications. The typical HHV of torrefied biomass is in the range of 18-30 $MJ.kg^{-1}$, as waste such as torrefied olive mill waste, corn cobs, and oil palm fruit, with the highest energy value. Catalytic torrefaction could also be explored to improve the properties and energy value of agricultural waste biomass. Process optimization of factors such as temperature, residence time, pressure and gas carrier is also essential in getting an improved calorific value with optimal mass and energy yield.

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