Journal of Energy Technologies and Policy
ISSN 2224-3232 (Paper) ISSN 2225-0573 (Online)
Vol.14, No.2, 2024

Enhancing herbaceous biomass pellets quality by blending with woody biomass and plastic additives, and post-pelletization torrefaction and optimization processes: A review

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Abstract

Current research emphasizes the use of assorted biomass resources of varying quality for pelletizing. Biomass pellet fuel is one of the most common and essential ways of harnessing biomass energy. Herbaceous biomasses like corn stovers, switchgrass and miscanthus are abundant in nature and when used to produce pellets, they are of low quality. This study provides an overview of methods for enhancing herbaceous biomass pellets quality through blending with woody biomasses like pine, eucalyptus and spruce saw dusts, use of plastic additives like linear low-density polyethylene and low-density polyethylene, post-pelletization torrefaction, and production of pellets at optimum conditions. The review revealed that the use of biomasses from wood and plastics as additives to herbaceous biomass, improved the pellet properties like strength, durability and higher heating values to great extents, while ash contents decreased. Post-pelletization torrefaction studies showed that there was a noticeable improvement in higher heating value. Finally, there was a general improvement of pellet qualities when pellets are produced at optimum conditions as depicted by the review of optimization studies on pelletization. Generally, each of these methods improves the pelletization of herbaceous biomass to different extents. Some studies have focused on combination of two or three of these methods in which the pellet properties are further enhanced. Therefore, there is need to explore the combination of these methods reviewed to produce pellets and evaluate them against internationally set pellet standards for commercialization.

Keywords: Herbaceous, woody biomass, plastic additives, torrefaction, optimization, pellets
DOI: 10.7176/JETP/14-2-02
Publication date: February 28th 2024

1. Introduction

Fossil fuel energy currently dominates world energy supply (Liu et al., 2022), standing at about 80% of the total primary energy supply (GLOBAL BIOENERGY STATISTICS 2022 World Bioenergy Association, 2022) as illustrated by Figure 1. 1a. The rapidly increasing advancement in development resulting from ballooning population has pushed energy demand up by greater margins leading to excessive use of oils, gas and coal (Haq et al., 2021; Liu et al., 2022). Consumption of these fuels have detrimental effects on the environment because of the high CO_2 emissions that lead to the greenhouse effect (Anukam et al., 2020; Hu et al., 2018; Liu et al., 2022; Pantaleo et al., 2020). Consequently, excessive production and use of these fuels leads to their depletion with time because of their non-renewability nature. These challenges have led to shift of focus to research, development and utilization of alternative sources of energy (Ali et al., 2021; Dujmović et al., 2022; Liu et al., 2022; Niedziółka et al., 2015; Picchio et al., 2020a). Biomass being one of them is not yet fully utilized along with solar, wind, geothermal, tidal and hydro (Dujmović et al., 2022; Jeguirim et al., 2019).

Biomass does not increase the net atmospheric carbon dioxide as it is illustrated in the carbon cycle (Figure 1. 2) and it offers a variety of uses (Koondhar et al., 2021) through its derived products which include methanol, ethanol, biodiesel, Fischer-Tropsch hydrogen, methane, fuelwood, charcoal, pellets and other biofuels (Alizadeh et al., 2020; Ambaye et al., 2021). Cui et al. (2021) also observed that using biodegradable and agricultural wastes as fuel alternatives reduces emissions from landfills and combustion. In this scenario, biomass has a lot of potential as a long-term, renewable source of bioenergy.

Utilization of biomass as renewable energy has, however, been faced with challenges such as: wide dispersion, irregular shape, low heating value, high moisture content (Ali et al., 2021), low bulk density and others consequently, leading to high handling, transportation and storage expenses (Ali et al., 2021; He et al., 2018). Drying, pelletizing and briquetting, torrefaction and use of binders are pretreatment and enhancement techniques of production of quality solid biomass fuels (He et al., 2018).

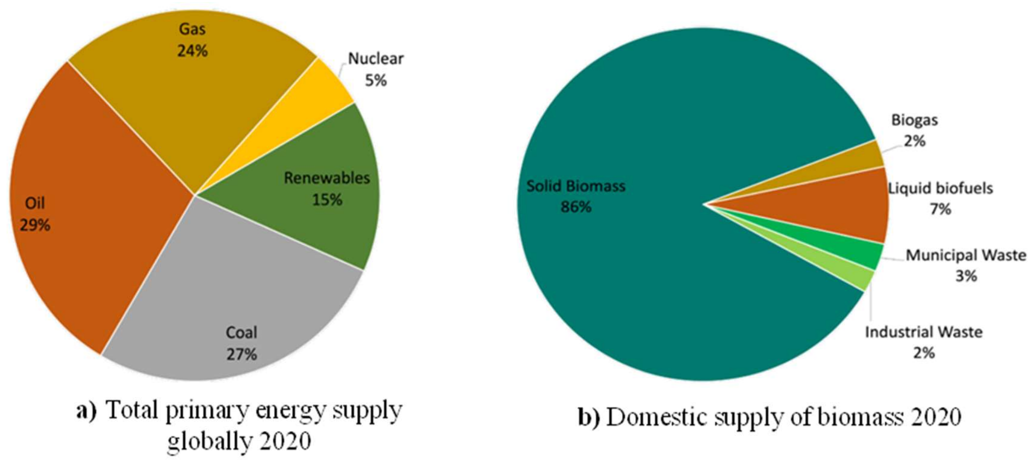

Figure 1. 1: a) Total primary energy supply and b) domestic biomass supply 2020 (GLOBAL BIOENERGY STATISTICS 2022 World Bioenergy Association, 2022).

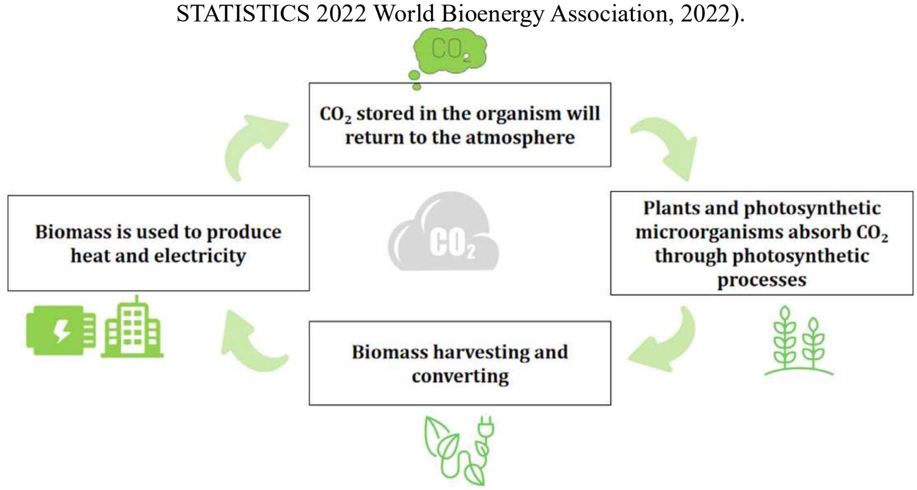

Figure 1. 2. Carbon cycle (Cui et al., 2021)

The chemical and physical features of various biomass feedstocks can be complimented and coordinated by blending different feedstock types in order to optimize the pelletizing processes and qualities through co-pelleting (Pradhan et al., 2018a). Co-pelletizing (combining various raw materials to produce pellets) is perceived to be potential in enhancing biomass pellet when sustainable, affordable and ecofriendly raw materials are utilized. Subsequently, co-pelletizing emerges as a viable alternative for optimizing performance of production of biomass pellet fuels (Cui et al., 2021). Additionally, co-pelletizing through blending various materials and optimizing pelletizing variables appear to be viable approaches to producing quality pellets. The strength of biomass pellets and the durability of the bonds of biomass particles are the most desired parameters in pellets (Agu, 2018). Pelleting temperature is critical in promoting strong bonding by enhancing chemical restructuring of biomass particles (Anukam et al., 2021; Henriksen et al., 2008; Ma et al., 2021; Riva et al., 2019). An in-depth understanding of the feedstocks of biomass that can be used in pelletization is, therefore, paramount and a prerequisite for researches on biofuels. This will be followed by the study of pellet production techniques, important pellet qualities and the methods used to improve the qualities of pellets.

2. Biomass raw materials

Biomass includes all organic material in the biosphere, be it of plant or animal nature, and also those derived from natural or artificial conversion (Koondhar et al., 2021; Perea-Moreno et al., 2019). Rozzi et al. (2020) and

Antar et al. (2021) also described biomass as non-fossil organic material with inbuilt carbon dioxide that has the ability to help mitigate greenhouse gas emissions.

Suitability of biomass for conversion to different biofuels is determined by assessing it properties through characterization (Cheng et al., 2016). Some useful biomass characterization methodologies include Transmission electron microscopy (TEM), X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FT-IR), atomic force microscopy (AFM), and scanning electron microscopy (SEM), depending on the desired biofuel application. In order to get proper understanding of biomass and the process of its conversion to biofuel, it is recommended that characterization is done before and after the treatment process ("Biotechnological Applications of Biomass," 2020).

Lignocellulosic biomass (LCB) is a common name used to refer to biomass (Cheng et al., 2016), is made up of various proportions of major chemical compounds including lignin, cellulose, and hemicellulose, constitute a large part of the chemical components in biomass residues as illustrated in Figure 2. 1. Additionally, the minor compounds include: extractives, water, proteins and inorganic elements such as potassium, calcium, aluminum, sodium and silicon, among others. These chemical structures are different from each other resulting in different chemical properties (Tursi, 2019) and, thus, establish the properties of the whole biomass.

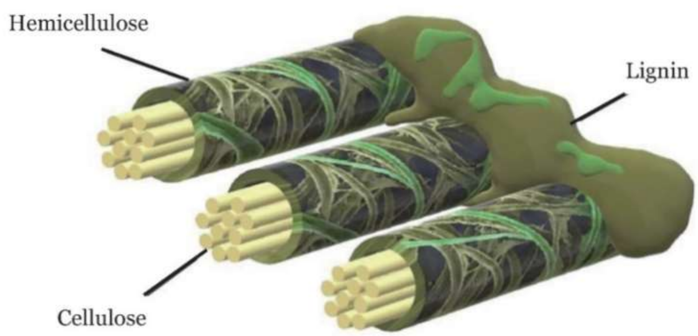

Figure 2. 1:Lignocellulosic biomass representation (Tursi, 2019)

2.1 Biomass characterization

Biomass proximate evaluation and its ultimate analysis are the main expressions of biomass characterization when biomass is used for biofuel production applicable in thermochemical processes (Anukam & Berghel, 2020.). Thus, higher heating value (HHV) should be considered in characterization.

2.1.1 Proximate analysis

A summary of the biomass's moisture, ash, volatile matter, and fixed carbon (FC) levels describes the proximate analysis of biomass (Adeleke et al., 2021). These properties have a significant effect on combustion of biomass feedstocks (Sivabalan et al., 2021), as well as production of solid biofuels through densification (Adeleke et al., 2021). As pertains combustion, moisture content determines the amount of heat energy required for ignition of fuel, whereas, slagging and fouling phenomena in boilers are a result of ash melting temperature and elements of ash. The ability of biomass feedstock to bond together to produce solid biofuels is greatly affected by its moisture content. It acts as a binder during densification when used in its optimum level. Lower and higher moisture levels lead to challenges in adhesion of biomass particles hence difficulty in densification (Garcia-Maraver, 2015a). According to Liu et al. (2022) the amount of moisture in feedstocks from biomass can be adjusted to optimum level by addition of water. Volatile matter and fixed carbon determine the higher heating values for both combustion and densification processes.

2.1.2 Ultimate analysis

The goal of ultimate biomass analysis is to evaluate the percentage of elemental ingredients, such as nitrogen (N), sulfur (S), carbon (C), hydrogen (H), oxygen (O), and other elements, that are present in biomass. Understanding these components makes it easier to calculate the volume and make up of combustion gases and also the amount (theoretical) of air needed for complete combustion. Typically, biomasses' heating value is established using various methods depending on this analysis (Dash et al., 2015). The atomic ratio classification—which comprises hydrogen, oxygen, and carbon—helps determine the fuel's heating value. For instance, there is a strong correlation between the oxygen-to-carbon (O/C) ratio and the biomass higher heating value (Dash et al., 2015). Gummert et al. (2019) also concluded that biomass having elevated sulfur and nitrogen composition results in generation of harmful gasses like nitrogen oxides (NOx) and sulphur oxides (SOx) during combustion, which are the major causes of acid rain and particulate matter emissions (PM).

2.1.3 Higher Heating Value (HHV)

Sivabalan et al. (2021) defined higher heating value as the total amount of energy produced by a unit of mass of fuel when completely combusted. The generated heating value is influenced by the chemical fuel elements.

Biomasses are unique in nature in that they posses' different chemical compositions and other characteristics. These leads to grouping of biomasses according to similarities in their characteristics. In the study on compositional analysis of biomass for production of renewable biofuels and chemicals, Williams et al. (2017) analyzed the chemical composition of biomass, both herbaceous and woody, municipal solid wastes and agricultural wastes and found that specific properties were within specific ranges for their respective biomass types. Biomass characteristics considered in this classification are ultimate and proximate analysis as well as structural carbohydrates. These types of biomasses inform the best method of utilization of biomass as biofuels.

2.1.4 Prediction of biomass properties using ultimate and proximate analysis

Ultimate and proximate analysis, as well as higher heating values of biomasses, are important thermochemical properties which are usually determined experimentally using various equipment. The challenge with experimental determination of these properties, as reported by Xing et al. (2019) is that its time-consuming, expensive, equipment unavailability and prone to experimental errors. Another essential biomass property is the structural carbohydrates such as lignin, cellulose, and hemicellulose. Nimmanterdwong et al. (2021) noted that tedious laboratory analytical procedures employing expensive equipment such as HPLC (High-performance liquid chromatography) and use of strong acids which raises concerns in terms of safety and accuracy are used in analysis of these structural carbohydrates. One outstanding solution that has been developed to eliminate the above highlighted challenges is the development of prediction models from correlations among various biomass properties (Nimmanterdwong et al., 2021). Datasets of ultimate and proximate analysis from various biomasses are used to predict other properties like HHV, cellulose, hemicellulose, lignin and either proximate analysis to estimate ultimate analysis or vice versa. Artificial Intelligence (AI) method of Machine Learning (ML)-based prediction models are often used to predict complex nonlinear regression tasks (Moayedi et al., 2019). Artificial neural network (ANN), logistic regression (LR), random forest (RF), support vector machine (SVM), genetic algorithm (GA), particle swarm optimization (PSO) and multi-linear regression (MLR) are examples of the commonly used ML algorithms (Ceylan & Sungur, 2020; Park et al., 2023).

Some of the studies that have applied prediction models to estimate biomass properties include; Park et al. (2023) estimated higher heating value using proximate or ultimate analysis. Krishnan et al. (2019) also used proximate analysis to estimated biomass' HHV. Park et al. (2023) developed a model to estimate the amounts of lignin, cellulose, and hemicellulose from ultimate and proximate analyses. Ceylan & Sungur (2020) estimated ultimate analysis from proximate analysis. In all these studies, the conclusion is that the errors of estimation were minimal and, therefore, the models can be used for future use.

These models for predicting biomass properties have different performance capabilities. In the research done by Ghugare et al., (2017), it was found out that nonlinear models developed from Artificial Neural Network (ANN), Genetic Programming (GP- extension of GA) and Support Vector Creation (SVC) to predict the quantities of Carbon, Hydrogen and Oxygen in biomass from their proximate analyses outshined their linear counterparts. In general, Random Forrest (RF) model accurately predicted biomass properties compared to others (Dubey & Guruviah, 2022; Y. Wang et al., 2022; Xing, Luo, Wang, & Fan, 2019).

2.2 Types of biomasses

Biomass can be classified using various criteria. The most widely accepted criteria are categorization based on origin (Demirbas et al., 2017; Nunes et al., 2020) resulting in biomass types, such as: wood and woody biomasses, herbaceous biomasses, aquatic biomasses, animal and human waste biomasses and mixtures of biomasses. In addition, Islas et al. (2018) included municipal solid waste as another type of biomass which encompasses wastes of cardboard, paper, plastic, textile, glass, wood and food. According to Tursi (2019), trees, shrubs and their residues are forms of wood and woody biomass. Herbaceous biomass has non-woody stem and are generally classified to agricultural residues and energy crops. Algal biomass forms aquatic biomass, while manure from animals and human excreta are examples of animal and human wastes. Finally, feedstocks containing the different types of biomasses are categorized as biomass mixtures. Figure 2. 2 illustrates biomass types and their selected examples.

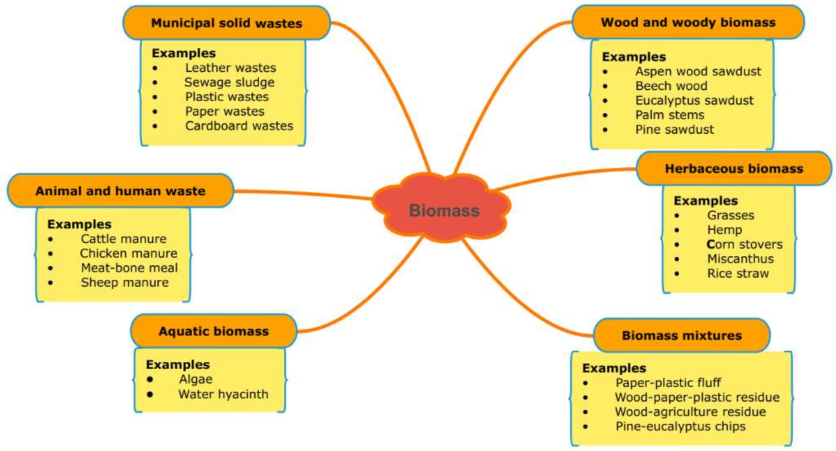

Figure 2. 2: Biomass types

2.3 Biomass as feedstock for biofuel production

Solid, liquid or gaseous fuels derived directly or indirectly from biomasses is referred to as the 'biofuel' (Sánchez et al., 2018) and according to Ruan et al (2019) it is applicable in production of heat, energy, power and light. In essence, chemical, physical, thermochemical and biochemical technologies are used to manufacture biofuels (Ruan et al., 2019). Ruan et al. (2019) realized in the study on biofuels that one type of biomass feedstock can be used in production of different varieties of biofuels using different techniques, hence, the diversity and the robustness of production of biofuels from biomass. He et al. (2018) and Sitek et al. (2021) discovered that compared to raw biomass fuels, biomass solid fuels emit very little particles and have a higher energy density. Furthermore, regular shape and dimensions allow for convenient handling, compact storage, and reliable feeding in large-scale applications.

There are many distinct kinds of solid fuels made from biomass, but the most popular solid biofuels types are pellets and briquettes (Pradhan et al., 2018a). Briquettes should have a diameter of more than 25 mm, while pellet fuels should have a diameter of at most 25 mm, as determined by the application of each one of them (Cui et al., 2021). When briquettes and pellets are compared, there are differences in production methods and market demands (Pradhan et al., 2018a). The difference between pelleting and briquetting production process is in the size of their dies. Briquettes and pellets are produced densely from biomass resources at a predetermined pressure and temperature (Pradhan et al., 2018b). Briquettes are typically cylindrical and range in size from 75 to 300 mm in diameter and length, respectively. They can be utilized in medium to large industrial thermal facilities and are larger than pellets (Dinesha et al., 2019). The majority of pellets have a diameters between 6-8 mm and a maximum length of 40 mm. They are common in small appliances like domestic cookers and gasifiers (Pradhan et al., 2018b).

Solid biomass accounts for 86% (Figure 1. 1b) of the supply of domestic biomass fuels (GLOBAL BIOENERGY STATISTICS 2022 World Bioenergy Association, 2022) which are mainly derived from wood and herbaceous biomass as well as municipal solid wastes. There are numerous types of wood and woody biomass that is used for solid biofuels. Pellets, wood shavings, woodfuel, sawdust (Kiang, 2018; Sharma et al., 2019) and commercial forestry (hog fuel) as well as other wood residues (Tumuluru & Fillerup, 2020) are typical examples of solid biofuels derived from the category of wood and woody biomasses. Agricultural wastes, like corn stover, miscanthus, switch grass among others are herbaceous biomasses that have distinct chemical properties from those of woody biomass (Popa, 2018). Thus, herbaceous biomass contains more ash but less lignin and carbon, whilst woody biomass contains more lignin and carbon but less ash. According to Kiang (2018), pellets from wood are known to possess superior qualities such as ultimate and proximate analysis, as well as higher heating value than herbaceous biomass.

3. Pellet production and important pellet properties and process parameters

Loosely packed, prepared biomass are compacted to uniformly sized biomass particles called pellets by process of densification (Adeleke et al., 2021), through the technologies described by (Vaish et al., 2022) which include: extrusion, hydraulic piston presses, screw presses, piston type presses, roller presses, and pellet presses (ring and flat die). The resultant pellet will be of high calorific value, consistent size, easy to handle, transport and store (Adeleke et al., 2021). Generally, the bulk densities of herbaceous biomasses are between 80-150kg/m^3, while that of woody biomasses are between 150-200kg/m^3 which are considered to be low (Japheth. et al., 2019). On densification through pelleting, these densities are improved to 600-800kg/m^3 (Garcia-Maraver, 2015a). Some of the most widely used pelleting technologies are described below.

3.1 Pellet mills
Pellet mills, also referred to as pellet presses or extruders, are machines that use high pressure to force biomass feedstock through the die's holes, causing friction and the temperature of raw materials to rise and reshaping it into pellets (Garcia-Maraver, 2015a). Depending on the shape of the die, pellet mills can be classified as either flat or round. In flat die pellet mills, the feedstock is placed on top of a die that has holes in it. When the die starts to rotate, the raw material is squeezed and forced through the openings of the die, whereupon the pellets are eventually cut. Such mills are used to produce pellets on a small- to medium-scale (Garcia-Maraver, 2015a). In contrast, round die pellet mills have round holes that are positioned vertically along the die. The raw material is placed in the die's center and distributed evenly throughout the process. The material is then squeezed through the perforations by the rollers, and the pellets are chopped by the die's outside blades.

3.2 Single pellet presses (SPP)
This is a bench scale pelletizing machine consisting of a cylindrical die manufactured from hardened steel (Puig-Arnavat et al., 2016), having diameters ranging from 3 to 25 mm (Japheth. et al., 2019) and equipped with heaters, thermal insulations, a hydraulic press, a tightly fitting piston as well as thermocouple integrated with control system for die temperature control. The biomass feedstock is compressed by pressing it against a stationery backstop using hydraulic press. It is usually difficult to control temperature resulting from friction in pellet mills making it hard to study specific quality parameters of the pellets (Mostafa et al., 2019). To overcome this challenge, single pellet presses are useful (Hosseinizand et al., 2018; Huang et al., 2017a; Stasiak et al., 2017).

3.3 Process variables for pelletization
Process variables, including particle size, binders, moisture content, and other machine settings, for instance, die speed, channel length, die diameter, and pressure gap have the most impact on pelletization (Pradhan et al., 2018a). These process factors are as discussed below.

3.3.1 Moisture content
Zamorano et al. (2011) noticed that a product's net HHV as well as the efficiency of combustion are both impacted by the amount of moisture in the product. High-moisture pellets lose dry matter, while being stored and transported, and they decompose quickly (Graham et al., 2017). Through review of several research papers, Pradhan et al. (2018a) found out that in a single pellet press, 10% moisture concentration is ideal for pelletization and that pellet density decreases as moisture content rises. Anukam et al. (2021) also suggests that addition of 7-10% water to dried biomass increases the pellet's quality. Hence, the conclusion that moisture content is among the key factors influencing pellet quality.

3.3.2 Particle size
Pelletization pressure is influenced by biomass particle size. Most experimental cases studied on single pellet presses established that a reduction in particle size resulted in an increase of pellet density, while pelletizing using ring die or flat die machines have insignificant effect regarding pellet density (Pradhan et al., 2018a).

3.3.3 Feedstock composition
In lignocellulosic biomasses, cellulose has a semi-crystalline structure and is resistant to hydrolysis, but hemicellulose has a random, amorphous structure with little strength and is easily hydrolyzed. The adhesive substances produced by hemicellulose hydrolysis are assumed to be the cause of natural bonding (Tumuluru et al., 2011). Moreover, lignin aids in the creation of solid bridges when temperatures are high and is important in biomass pelletization. Tumuluru (2014) showed that solid bridges are primarily responsible for particle bonding in pictures from a scanning electron microscope (SEM). At the right temperatures and moisture content, natural binders like lignin, proteins, and starch create solid bridges. Furthermore, Low molecular hydrocarbons, such as oils, waxes, and other extractives, reduces wall friction and subsequently the pelletization pressure because their concentration on the pellet surface rises when the temperature is raised. The glass transition of lignin, followed by flow and hardening, results in pellets of greater quality. At high temperatures, lignin is expected to soften and act as a binding agent. Because lignin serves as a binder, biomass with a higher lignin content produces more durable pellets.

3.3.4 Machine specific parameters
Some machine-specific features that affect the pelletization process include: die size, speed, temperature and pressure gap (Pradhan et al., 2018a).

3.4 Fundamental pellet qualities
3.4.1 Durability

Alakangas (2011) defined Mechanical durability (also known as abrasion resistance) as the capacity for handled densified biofuels to maintain their original form. It is determined by how well densified fuels can withstand shock or friction. Because the pellet is prone to mechanical wear, it generates dust or fine particles when being transported and stored. The pellets' ability to generate dust throughout its handling, transit, and storage will be revealed by the resistance test. Consumers are inconvenienced by dust emissions, which also endanger their health. Furthermore, dust and small particles may clog boiler feeding systems, which leads to uneven combustion processes. Lastly, dust can cause fire and explosive hazards during handling, storage, and transportation (Vinterbäck, 2004).

Pellets from various types of biomasses have different durability indexes resulting from their different compositions. Blending these biomasses to produce pellets, have unique effects on pellet durability depending on the chosen blends as demonstrated by (Rajput et al., 2020), in the study on methods to improve pellets' fuel qualities. The author found out that addition of sawdust which is woody biomass to groundnut shells and leaf litter wastes which are herbaceous biomass increased pellet durability. This was linked to higher lignin content in sawdust than in both groundnut shells and leaf litter wastes. There was reduction of pellet durability when groundnut shells were added to sawdust. Torrefaction after pelletization is an essential process that affects the durability index of the pellets. Sarker et al. (2022) showed that the durability index of the pellets is decreased when pellets are torrefied while the calorific value is increased.

3.4.2 Hardness

Hardness determines the maximum crushing stress (or compressive or crushing resistance) that a pellet may withstand before breaking or cracking (Kaliyan & Vance Morey, 2009). Tensile strength is correlated with the adhesion forces between particles at all points of contact in an agglomeration. A compressive resistance test replicates compressive stress caused by pellet crushing in a screw feeder, and also the weight of upper pellets on lower pellets when they are stored in silos or bins (Garcia-Maraver, 2015b).

The research on the impacts of post-pellet torrefaction on pellet strength and fuel characteristics by Haykiri-Acma & Yaman (2022), revealed that the pellet strength decreases in this process compared to raw pellets. The same phenomenon was also observed by Sarker et al. (2022). Concerning pellet hardness, Rajput et al. (2020), observed that pellets produced from pure woody biomass have higher hardness than others. Therefore, woody biomass may be used as an additive to improve the hardness of pellets from other types of biomasses. The loss of pellets' strength and durability after torrefaction is attributed to degradation of hemicellulose and cellulose (Wang et al., 2020).

3.4.3 Bulk density

The pellets' bulk density is a measurement used for stockpiling of wood fuels because spaces between the woody particles may be greater or smaller, based on the size and form of the pellets. Non-densified biomass is bulky, making long-distance transport challenging and necessitating storage space. Furthermore, because the fuel is fed by volume rather than weight, bulk density can have a notable impact on combustion efficiency (EN15103, 2009). Among the variables that affects bulk density include torrefaction after pelletization. The bulk density generally decreases on torrefaction of pellets (Manouchehrinejad & Mani, 2018; Siyal et al., 2021). In the study of improvement of agro-pellet quality through blending, Park et al. (2020), observed that the bulk densities are generally higher for blended pellets than single strand pellets.

3.4.4 Particle density

According to Sarker et al. (2023), particle density is mass-to-volume ratio of a single pellet. Its value is affected by the particle size, compression strength, protein content, and moisture content. This characteristic affects the bulk density and, consequently, the characteristics of combustion of the pellets such as heat conductivity, burning rate and degasification rate. Stasiak et al. (2017) found out that the particle density of pellets produced from blends of pine sawdust and straws was higher than when produced from pure biomasses, hence, the importance of blending in pellet production. Similar observation was made by (Serrano et al., 2011). According to Siyal et al. (2021), torrefaction adversely affects pellet particle density. Therefore, one can draw a conclusion from it that, blending different biomasses improves pellet particle density while torrefaction decreases it.

3.4.5 Size of the pellets

An important parameter in size of the pellets is the length/diameter ratio which affects moisture uptake of pellets in humid environments and is of great importance on feeding to the combustion chambers (Hartley & Wood, 2008). According to Mostafa et al. (2019), biomass pellet demand has increased recently, which has led to increase in the price of woody biomass and, hence, its scarcity because of exploitation for pellet production. Therefore, to curb this challenge, non-woody, herbaceous and other biomasses (Figure 2. 2) have received greater attention and research for pellet production. However, pellets produced from biomasses other than woody biomass possess poor qualities (Picchio et al., 2020b). Due to the dwindling woody biomass quantities, resulting from deforestation and the many utilities of wood, other biomasses have emerged to have a greater potential in production of biofuels.

Herbaceous biomasses are the most abundant and underutilized biomasses. To use these biomasses to produce quality pellets, quality enhancement methods have to be incorporated to elevate their properties to acceptable international standards.

4. Methods of biomass pellet quality enhancement

4.1 Use of woody biomass as an additive

Gilvari et al. (2019) tied pellet quality to biomass type. The shortcomings of herbaceous biomass regarding the physical property (lower density), chemical makeup (higher ash, lower carbon, and lower lignin), and fuel property (lower heating value) could be resolved by blending with woody biomass (Picchio et al., 2020a; Tumuluru & Fillerup, 2020). In the study on co-pelletization, Cui et al. (2021) concluded that addition of woody biomass to straw (herbaceous biomass), to produce pellets, improved significantly pellet qualities. For instance, according to Tumuluru et al. (2012), it significantly enhances proximate and ultimate composition whilst also reducing the amount of ash in pellets. The study also reports that addition of woody biomass enhances the densification properties of herbaceous biomass because of its higher lignin content that is the primary binder in pelleting/briquetting.

In the review on biomass pelleting process, Dujmović et al. (2022) reported that addition of woody biomass on agricultural biomass produced pellets with enhanced physico-mechanical properties and this was affirmed by pellets from cornstalk blended with fir. Contrary, addition of herbaceous biomass to woody biomass as studied by (Lehmann et al., 2012) has a negative effect on durability of biomass that has been densified and it revealed that the pellet's density reduces.

Table 4. 1 Presents the observations of the effect on pellet properties caused by blending herbaceous biomass with woody biomass.

4.2 Use of plastic additives

According to Anukam et al. (2021), all biomasses can be pelleted, but not all are able to produce high-quality pellets. As a result, additives are utilized to enhance pelletization. Lignosulfonates, spent sulfite liquor, starch, kraft lignin, waste vegetable oils, and citrus peels are additives discussed by Anukam et al. (2021). Other additives include plastics (Auprakul et al., 2014). Emadi et al. (2017) stated that linear low-density polyethylene (LLDPE) and low-density polyethylene (LDPE) are the most abundant types of plastics which can be easily derived from municipal solid wastes (MSW) and have favorable fuel and adhesion properties. Thus, according to Emadi et al. (2017), the use of LLDPE as additives results in pellets with high density, strength and higher heating value, and decreased ash content. High density polyethylene (HPDE) is also extractable from MSW (Agu et al., 2021). HDPE, according Agu et al. (2021), significantly increases higher heating values of pellets produced from torrefied and non-torrefied wheat and barley straws. It also increases pellet strength and durability of pellets as well as pellet particle density. Although the pellet particle density was seen to improve, it was not to the extent, when LLDPE is used as a binder. Ash content and moisture adsorption of biomass pellets are greatly reduced when HDPE is used as a binder (Agu et al., 2018). Generally, plastic binders enhance the bulk densities, mechanical strength and higher heating values as depicted by researches presented in Table 4. 2.

Table 4. 1: Researches on effect of addition of woody biomass to herbaceous biomass for pelleting

Sr No.	Feedstock blends		Observation	References
	Herbaceous biomass	*Woody biomass*		
1	Switch grass	Pine	Increased bulk density and durability.	(Tumuluru, 2019)
2	Rice straw	Sawdust	Increased unit density and shatter index. Higher heating value increased by 6-7.2%.	(Rahaman & Salam, 2017)
3	Barley straw	Pine sawdust	Pellet durability increased by 3%.	(Serrano et al., 2011)
4	Miscanthus	Pine sawdust	Improved thermal properties. Decreased ash content.	(Mohammadi & Anukam, 2023)
5	Rapeseed straw and wheat straw	Pine sawdust	Pellets strength and higher heating value decreased with increase in straws ratio. Pellet density decreased with increase in straws ratio. Increased straw proportion increased the ash content of the pellets.	(Stasiak et al., 2017)
6	Miscanthus and switch grass	Pine sawdust	Pellet met industrial quality with switchgrass and miscanthus blends of less than 30%.	(García, Gil, Rubiera, et al., 2019)
7	Reed canary grass, timothy hay and switchgrass	Spruce and pine sawdust	Improved overall pellet quality. Lowers pelleting energy requirement.	(Harun et al., 2018)

4.3 Use of TAP (Torrefaction After Pelletization)

Torrefaction is one method for improving the properties of solid biomass which has gained popularity. It is a mild thermochemical treatment used on biomass at ambient pressure in low-oxygen environment (Mukherjee et al., 2022; Nunes et al., 2014; Tumuluru et al., 2021) at temperature ranges of 200-300^{O}C and residence time of 30-180 minutes (Fisher et al., 2012; García, Gil, González-Vázquez, et al., 2019; Shang, Ahrenfeldt, et al., 2012). The results of torrefaction in this kind of environment are decomposition of hemicellulose partially to volatile matter and removal of all the moisture in biomass while lignin content and cellulose are unaffected (García, Gil, Rubiera, et al., 2019).

The most important process conditions for optimum energy yield in torrefaction from past researchers are torrefaction temperature, time and the size of biomass particles (Adeleke et al., 2021; Akanni et al., 2019).

Table 4. 2: Researches on effect of plastic additives biomass pelleting

Sr No.	Feedstock blends	Observation	References
1	Torrefied wheat and barley straws and LLDPE	Increased higher heating value. Increased mechanical strength. Decreased ash content.	(Emadi et al., 2017)
2	Corn stover and mixed plastic wastes	Carbon, hydrogen and higher heating value increased with increase in plastic content. Durability, bulk density, particle density and ash content decreased with increase in plastic content.	(Auprakul et al., 2014)
3	Refuse derived fuel with 20% plastic	Increased higher heating value. Improved mechanical strength.	(Rezaei et al., 2020)
4	Pinus radiata sawdust, LLDPE and polypropylene (PP)	Increased durability. Greatly improved hydrophobicity. Improves HHV moderately to highly.	(Song et al., 2021)
5	Sawdust, date palm trunk and plastic wastes	Increased durability index and bulk density as well as particle density. Overall, pellet produced attained acceptable standards.	(Garrido et al., 2017)
6	Torrefied wheat, barley straws and HDPE	Pellet density and tensile strength was improved. HHV increased. Hydrophobicity improved. Ash content decreased.	(Agu et al., 2021)

Chen et al. (2021) further narrowed down the conditions to temperature and residence time, while Akanni et al. (2019) again further narrowed down to only torrefaction temperature, stating that the effect of residence time reduces after one hour of torrefaction. Thus, further pointing out that as torrefaction temperature rises the mass and energy yields decreases leading to increase in energy density.

Torrefaction can be employed as a pre-treatment method of biomasses before pelletization commonly referred as TOP (Torrefaction before Pelletization) process or as a post-treatment after pelletization referred commonly as TAP (Torrefaction After Pelletization) process (Azargohar et al., 2018; Manouchehrinejad & Mani, 2018). The discussion of some researches on torrefaction after pelletization (TAP) processes are as follows: Manouchehrinejad & Mani (2018) studied the effect of torrefaction of wood pellets produced from mixed sawmill wastes of soft and hardwoods at temperatures of between 230^{0}C and 290^{0}C. The observation was that the shape of the pellets was retained, the mass and energy yields decreased with increasing torrefaction temperature. Higher heating values increased by 26%, as well as its hydrophobicity, while pellet particle and bulk densities, moisture, durability and hardness decreased. Wang et al. (L. Wang et al., 2020) found out that the torrefied pellets maintained their integrity while mass yield decreased with temperature increase, higher heating values and hydrophobicity increased. The mechanical properties of torrefied generally decreased with increasing torrefaction temperature. In their studies, Ghiasi et al. (2014), Shang et al. (2012) and Kumar et al. (2017) concluded that post-pelletization torrefaction resulted in improved higher heating value, energy density and hydrophobicity, while particle and bulk densities, mass and energy yields, as well as the mechanical properties of pellets, reduce with torrefaction. They also observed that the structural integrity of the pellets is maintained.

4.4 Optimization as quality improvement method

According to Mostafa et al. (2021a), the conditions of pelletization influence biomass pellet qualities. Thus, the exact effect of pellet production process parameters to give the best physico-mechanical and characteristics of combustion of pellets have to be determined. Data from optimization studies can then be utilized for subsequent production of quality pellets, hence, a quality enhancement method.

Liu et al. (2023) described process optimization as a condition in which several factors interdependently affect the outcomes in order to obtain a specific quality required. Optimization studies can be multi-parameter, multi-response, single response, single factor or a mix of them and analysis done using different statistical tools (Thapa et al., 2018).

Pellet qualities are maximum at optimum conditions of production (Cui et al., 2021). Pellet durability, hardness, bulk density and higher heating values are qualities used to determine the optimal process parameters in pellet production (Thapa & Engelken, 2020). These are desirable pellet qualities and, therefore, have to be maximized, so that it gives the best combination of process parameters. At the same time, undesirable pellet qualities like emissions have to be minimized. Said et al. (2015) observed that pellet quality is dependent on feedstock composition and controllable process factors. An example of controllable factors is moisture content, in which if it is high decreases the durability, higher heating values and shelf life of pellets, while increased binder concentration improves its durability (Akbar et al., 2021).

Various process parameters considered in optimization have been studied in literature and they include; feedstock material, moisture content, blending ratio, particle size, binders (Thapa & Engelken, 2020), and die pressure (Huang et al., 2017b; Mostafa et al., 2021a). It also includes torrefaction temperature and residence time (Akanni et al., 2019), in the case of torrefaction after pelletization studies. The shortcomings brought about by feedstock variability in terms of physical and chemical properties can be resolved by blending different biomass feedstocks (Edmunds et al., 2018; Ray et al., 2017). Tumuluru (2019) studied the effect of blending feedstock material from pine and switchgrass on the pellet durability and bulk density. The resultant pellet attained maximum durability index greater than 95% and bulk density of 550kg/m^3. In optimization study done by Thapa & Engelken (2020) using Taguchi-grey relational analysis, blending ratio, particle size, feedstock material and blending ratio were found to have significantly impacted on pellets physico-chemical characteristics. Park et al. (2021), in the study of performance optimization of fuel pellets, found out that the optimal ratio of pepper stem to coffee waste was 8:2 and the optimal torrefaction temperature was 250^{0}C. In the study, performance indicators used were moisture content, bulk density, durability, ash content, fines particles and gross calorific value. Zhang et al. (2020) researched on optimization of pellets produced from hydrothermally pretreated wheat straw using response surface methodology. The parameters studied included; wheat straw feedstock particle size, hydrothermal pressure and temperature, mold pressure, moisture content, compression speed and pressure holding time. Optimum pelletization conditions were as presented in **Error! Reference source not found.**. Conspicuously, in all the above studies, none of them analyzed emissions. Again, only one of the studies went ahead to include torrefaction after pelletization. **Error! Reference source not found.** presents biomass pelleting optimization studies carried out by different researchers and their outcomes on pellet quality.

Table 4. 3: Biomass pelleting optimization studies

Sr. No.	Feedstock	Pelleting technique	Statistical tool	Optimum conditions	Quality of pellet	References
1	Rice straw	Single pellet press (SPP)	Response surface method using multi-objective optimization approach.	72.76 MPa, 110°C, and 7.23% moisture for solid pellets.	Higher pellet quality	(Mostafa et al., 2021a)
2	Rice straw	Flat-die pellet mill	Full factorial design	2% starch additive, 17% moisture content, die temperature<50^{0}C and die size 8/32mm/mm (8mm diameter and 32mm compression length).	99.311% durability and most pellet qualities met set standards.	(Said et al., 2015)
3	Birch, Spruce Reed canary grass	SPP	Regression analysis Regression analysis Regression analysis	6.1%moisture, 300MPa and 400MPa. 5.1%moisture, 300MPa 5.2% moisture, 300MPa	Pellet density, strength and moisture met set standards	(Huang et al., 2017a)
4	Wheat straw	SPP	Box-Behnken design	35 days for *Phanerochaete chrysosporium* (PC) and 21days for g *Trametes versicolor* 52J (TV52J) fungal treatments	Pellet density, dimensional integrity and tensile strength met the set standards	(Gao et al., 2017)
5	Biochar, sawdust and water	Pellet mill (unspecified type)	Box-Behnken design	40% biochar, 30% sawdust and 30%moisture	Higher pellet durability and heating value	(Bartocci et al., 2018)
7	Rice straw, wheat straw and cornstover	Flat die pellet mill	Taguchi-grey relational analysis	Order of parameters from those resulting in greatest effect are binder proportion>binder type>residue type>particle size	Improved overall pellet quality	(Thapa et al., 2018)
8	Corn stalk rinds	SPP	Box-Behnken design	0.5mm particle size, 11.35% moisture, 125.7 ^{0}C and 154.2MPa	1639.61 kg/m^3 Relaxed density, 97.95% durability and 10.18 MPa compressive strength.	(D. Liu et al., 2023)

9	Bagasse	Box-Behnken design	Biomass composition, molasses concentration and drying time	16.43 MJ kg^{-1} higher heating values and 84.2% durability	(Akbar et al., 2021)

5. Combustion emissions from pellets

Combustion of biomass pellet results in heat energy and different emissions. Perez-Jimenez (2015) provided a comprehensive classification and conditions of production of various gaseous emissions from combustion biomass pellets. The two major classes are gaseous emissions from complete and incomplete combustion. Examples of emissions emanating from incomplete combustion which included; CO, PAHs, NH_3, CH_4, total organic compounds (TOCs) and polychlorinated dioxins & furans. On the hand, emissions from complete combustion included; CO_2, SO_2, NO_x and hydrogen chloride. These emissions are harmful to the environment, humans and combustion equipment.

Quantity of emissions from different biomass feedstocks vary since their compositions are unique. In the case of pelleting and briquetting, the type and amount of binder used also play an important role in emissions produced. Carroll et al., (2013) analyzed carbon monoxide (CO), sulphur dioxide (SO2) and nitrogen oxides (NOx) emissions from different biomasses and found out that those from woody biomass met the emissions standards (EU regulations) while those of straws which are basically herbaceous biomass exceeded the set limits. In the study on combustion of waste plastics, lignite and biomass mixture pellets, Duranay (Duranay, 2019) found that the rate of combustion and efficiency increased with the increase in plastic ratio. Also, CO_2 emissions increased with the increase in plastic ratio. Measures to reduce emissions have to be incorporated in combustion process of biomass fuels prone to emissions like feedstocks from herbaceous biomasses and fuel feedstocks with plastic binders.

6. Pellet quality standards

According to Garcia-Maraver (2015a), byproducts from combustion of pellets and their effects on combustion equipment like pellet stoves and boilers, are among the important customers concerns other than pellets' energy content. It is also important to appreciate the fact that biomass fuel pellets derived from several feedstocks of biomass produced from different processes are unique. In order to ensure the best quality pellets are produced, quality control and standardization has been introduced in many countries (Japheth et al., 2019; Mostafa et al., 2021b). These standards have ranges of different properties of pellets that define the acceptable quality of pellets (Mostafa et al., 2021a). Biomass pellet standards and their general requirements have been produced for different types of biomasses and even their mixtures (Mostafa et al., 2019). For instance,

Table 5. 1 illustrates the European guidelines EN 14961-6 pellets for non-woody biomass pellets or pellet mixtures from different biomasses. Pellets from non-woody biomass are categorized as A class, while those from mixtures of different biomasses are B class pellets (Garcia-Maraver, 2015a). Pellet quality parameters are compared to these standard specifications so as to evaluate the overall quality of the pellet produced. According to Garcia-Maraver (2015a), some of the European Pellet quality standards and certification include:

1. Austrian standard: ÖNORM M 7135 (Compressed wood or compressed bark in natural state, pellets and briquettes. Requirements and test specifications: 2003).
2. Swedish standards: SS 187120 (Biofuels and peat, fuel pellets. Classification (Swedish Standards Institution): 1998.).
3. German standards: DIN 51731 (Testing of solid fuels, compressed untreated wood. Requirements and testing (Deutsches Institut für Normung): 1996.).
4. Italian standard: CTI-R04/05 (Recommendation: solid biofuels. Pellet characterization for energetic purposes: 2004.).
5. French recommendation: ITEBE (Not official standard but set of quality controls developed. 2009).
6. European standard committee EN14961-1 (Solid biofuels. Fuel specification and classes. Part 1: general requirements: 2010.).

Table 5. 1: European normative guidelines for pellets produced from herbaceous and fruit biomass and blends and mixtures (Garcia-Maraver, 2015a)

Pellet property	Units	Straw	Miscanthus	Reed canary grass
Diameter and length, D and L	Mm	D06-10: D±1; 3.15≤L≤40 D12-25: D±1; 3.15≤L≤50		
Moisture, M	% as received	M10≤10		M12≤12
Ash, A	% dry basis	A6.0≤6 A6.0+>6	A4.0≤4	A8.0≤8 A8.0+>8
Mechanical durability, DU	% as received	DU97.5≥97.5		DU96.5≥96.5
Fines	% as received	F1.0≤1.0		
Additives	% dry basis	Type and Quantity		
Lower heating value as received, Q	MJ/kg	Minimum value Q14.5≥14.5		
Bulk density, BD	Kg/m^3 % as received	BD600≥600	BD580≥580	BD550≥550
Nitrogen, N	% dry basis	N0.7≤0.7	N0.5≤0.5	N2.0≤2.0
Sulphur, S	% dry basis	S0.10≤0.10	S0.05≤0.05	S0.20≤0.20
Chlorine, Cl	% dry basis	Cl0.1≤0.10	Cl0.8≤0.8	Cl0.1≤0.10

7. Conclusions

From the review on biomass feedstocks, pellet production techniques and methods of biomass pellet improvement, the following conclusions can be drawn;

i. Before biomass pelletization research is carried out, preliminary tests of biomass feedstocks are done through various characterization techniques to determine their ultimate and proximate analysis and thereafter, characterization process is again carried out to ascertain the impact of pelletization on the biomass feedstocks.
ii. When pellet mills are used in pellet production, heat generated from the friction between the die and the rollers is difficult to control. Therefore, the best remedy to this in order to study the specific quality parameters is to use single pellet presses (SPP) which are capable of controlling different pelleting parameters accurately.
iii. Addition of woody biomass to herbaceous biomass in pelletization generally improved the properties of the resultant pellet. The bulk density, durability and higher heating values of the pellets were the most studied and it was found to increase with addition of woody biomass. Ash content on the other hand decreased.
iv. Use of plastic additives generally increases the pellet strength, durability and higher heating values with great reduction in ash content. LLDPE and LDPE are the most abundant plastics which have received little attention in use for biofuel production.
v. In TAP process, the structural integrity of the pellet is maintained and the higher heating values are greatly improved. It can also be concluded that the most significant factor is the torrefaction temperature in torrefaction studies on residence time of at least one hour.
vi. In use of optimization, as a quality enhancement method, generally the pellets produced possessed higher qualities which met the set pellet quality standards. Most of the optimization studies used single strand biomasses and optimized pelleting parameters. There are limited researches that incorporate optimization with multiple biomasses, plastic additives and TAP process which may result in a pellet with superior qualities.

Authors' contributions

Limo LK: conceptualization, data curation, formal analysis, investigation, validation, project administration, writing- original draft and writing- review and editing. DS Madara: conceptualization, validation, supervision and writing- review and editing. O Maube: conceptualization, validation, supervision and writing- review and editing.

Data availability

The data used in this research is available in the references cited.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Acknowledgements

The authors acknowledge ACE II-PTRE (Africa Centre of Excellence II – Phytochemicals, Textiles and Renewable Energy) Moi University for facilitation of research resources.

References

Adeleke, A. A., Odusote, J. K., Ikubanni, P. P., Lasode, O. A., Malathi, M., & Paswan, D. (2021). Essential basics on biomass torrefaction, densification and utilization. In *International Journal of Energy Research* (Vol. 45, Issue 2, pp. 1375–1395). John Wiley and Sons Ltd. https://doi.org/10.1002/er.5884

Adeleke, A., Odusote, J., Ikubanni, P., Lasode, O., Malathi, M., & Pasawan, D. (2021). Physical and mechanical characteristics of composite briquette from coal and pretreated wood fines. *International Journal of Coal Science and Technology*, *8*(5), 1088–1098. https://doi.org/10.1007/s40789-021-00438-0

Agu, O. S. (2018). Effect of binders on agricultural crop residues and wastes pellets. A review. *The Canadian Society for Bioengineering*, *CSBE18-116*, 1–9.

Agu, O. S., Tabil, L. G., Emadi, B., & Mupondwa, E. (2018). Microwave-assisted torrefaction of biomass: Effect of biochar and recycled polymer plastic (HDPE) on the physical quality of fuel pellets. *ASABE 2018 Annual International Meeting*. https://doi.org/10.13031/aim.201801398

Agu, O. S., Tabil, L. G., Mupondwa, E., & Emadi, B. (2021). Torrefaction and Pelleting of Wheat and Barley Straw for Biofuel and Energy Applications. *Frontiers in Energy Research*, *9*. https://doi.org/10.3389/fenrg.2021.699657

Akanni, A. A., Kolawole, O. J., Dayanand, P., Ajani, L. O., & Madhurai, M. (2019). Influence of torrefaction on lignocellulosic woody biomass of Nigerian origin. *Journal of Chemical Technology and Metallurgy*, *54*(2).

Akbar, A., Aslam, U., Asghar, A., & Aslam, Z. (2021). Effect of binding materials on physical and fuel characteristics of bagasse-based pellets. *Biomass and Bioenergy*, *150*(April), 106118. https://doi.org/10.1016/j.biombioe.2021.106118

Alakangas, E. (2011). European Standards for Fuel Specification and Classes of Solid Biofuels. *Green Energy and Technology*, *28*. https://doi.org/10.1007/978-1-84996-393-0_2

Ali, A., Liu, Y., Mao, X., Ali, Z., Ran, C., Ao, W., Fu, J., Zhou, C., Wang, L., Li, X., Liu, G., & Dai, J. (2021). Biomass and Bioenergy Co-pelletization of sewage sludge, furfural residue and corn stalk: Characteristics and quality analysis of pellets. *Biomass and Bioenergy*, *150*(May), 106121. https://doi.org/10.1016/j.biombioe.2021.106121

Alizadeh, R., Lund, P. D., & Soltanisehat, L. (2020). Outlook on biofuels in future studies: A systematic literature review. *Renewable and Sustainable Energy Reviews*, *134*(August), 110326. https://doi.org/10.1016/j.rser.2020.110326

Ambaye, T. G., Vaccari, M., Bonilla-Petriciolet, A., Prasad, S., van Hullebusch, E. D., & Rtimi, S. (2021). Emerging technologies for biofuel production: A critical review on recent progress, challenges and perspectives. *Journal of Environmental Management*, *290*(May). https://doi.org/10.1016/j.jenvman.2021.112627

Antar, M., Lyu, D., Nazari, M., Shah, A., Zhou, X., & Smith, D. L. (2021). Biomass for a sustainable bioeconomy: An overview of world biomass production and utilization. *Renewable and Sustainable Energy Reviews*, *139*(December 2020), 110691. https://doi.org/10.1016/j.rser.2020.110691

Anukam, A., & Berghel, J. (n.d.). *Biomass Pretreatment and Characterization: A Review*. www.intechopen.com

Anukam, A., Berghel, J., Henrikson, G., Frodeson, S., & Ståhl, M. (2021). A review of the mechanism of bonding in densified biomass pellets. *Renewable and Sustainable Energy Reviews*, *148*(August 2020), 111249. https://doi.org/10.1016/j.rser.2021.111249

Anukam, A. I., Berghel, J., Famewo, E. B., & Frodeson, S. (2020). Improving the Understanding of the Bonding Mechanism of Primary Components of Biomass Pellets through the Use of Advanced Analytical Instruments. *Journal of Wood Chemistry and Technology*, *40*(1), 15–32. https://doi.org/10.1080/02773813.2019.1652324

Auprakul, U., Promwungkwa, A., Tippayawong, N., & Chaiklangmuang, S. (2014). Densified fuels from mixed plastic wastes and corn stover. *Advanced Materials Research*, *931–932*(May), 1117–1121. https://doi.org/10.4028/www.scientific.net/AMR.931-932.1117

Azargohar, R., Nanda, S., & Dalai, A. K. (2018). Densification of agricultural wastes and forest residues: A review on influential parameters and treatments. *Recent Advancements in Biofuels and Bioenergy Utilization*, 27–51. https://doi.org/10.1007/978-981-13-1307-3_2

Bartocci, P., Barbanera, M., Skreiberg, O., Wang, L., Bidini, G., & Fantozzi, F. (2018). Biocarbon pellet production: Optimization of pelletizing process. *Chemical Engineering Transactions*, *65*. https://doi.org/10.3303/CET1865060

Biotechnological Applications of Biomass. (2020). In *Biotechnological Applications of Biomass*. https://doi.org/10.5772/intechopen.89320

Carroll, J., & Finnan, J. (2013). Emissions and efficiencies from the combustion of agricultural feedstock pellets using a small-scale tilting grate boiler. *Biosystems Engineering*, *115*(1). https://doi.org/10.1016/j.biosystemseng.2013.01.009

Ceylan, Z., & Sungur, B. (2020). Estimation of coal elemental composition from proximate analysis using machine learning techniques. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *42*(20), 2576–2592. https://doi.org/10.1080/15567036.2020.1790696

Chen, C. Y., Chen, W. H., & Ilham, Z. (2021). Effects of torrefaction and water washing on the properties and combustion reactivity of various wastes. *International Journal of Energy Research*, *45*(6). https://doi.org/10.1002/er.5458

Cheng, Y.-L., Lee, C.-Y., Huang, Y.-L., Buckner, C. A., Lafrenie, R. M., Dénommée, J. A., Caswell, J. M., Want, D. A., Gan, G. G., Leong, Y. C., Bee, P. C., Chin, E., Teh, A. K. H., Picco, S., Villegas, L., Tonelli, F., Merlo, M., Rigau, J., Diaz, D., … Mathijssen, R. H. J. (2016). We are IntechOpen, the world' s leading publisher of Open Access books Built by scientists, for scientists TOP 1 %. *Intech*, *11*(tourism), 13. https://www.intechopen.com/books/advanced-biometric-technologies/liveness-detection-in-biometrics

Cui, X., Yang, J., Wang, Z., & Shi, X. (2021). Better use of bioenergy: A critical review of co-pelletizing for biofuel manufacturing. *Carbon Capture Science and Technology*, *1*(September), 100005. https://doi.org/10.1016/j.ccst.2021.100005

Dash, M., Venkata Dasu, V., & Mohanty, K. (2015). Physico-chemical characterization of Miscanthus, Castor, and Jatropha towards biofuel production. *Journal of Renewable and Sustainable Energy*, *7*(4). https://doi.org/10.1063/1.4926577

Demirbas, A., Omar Al-Sasi, B., & Nizami, A. S. (2017). Recent volatility in the price of crude oil. In *Energy Sources, Part B: Economics, Planning and Policy* (Vol. 12, Issue 5). https://doi.org/10.1080/15567249.2016.1153751

Dinesha, P., Kumar, S., & Rosen, M. A. (2019). Biomass Briquettes as an Alternative Fuel: A Comprehensive Review. *Energy Technology*, *7*(5), 1–8. https://doi.org/10.1002/ente.201801011

Dubey, R., & Guruviah, V. (2022). Machine learning approach for categorical biomass higher heating value prediction based on proximate analysis. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *44*(2). https://doi.org/10.1080/15567036.2022.2065386

Dujmović, M., Šafran, B., Jug, M., Radmanović, K., & Antonović, A. (2022). Biomass Pelletizing Process: A Review. *Drvna Industrija*, *73*(1), 99–106. https://doi.org/10.5552/drvind.2022.2139

Duranay, N. D. (2019). CO2 emission from combustion of lignite, waste plastics and biomass mixture pellets. *Chemical Industry and Chemical Engineering Quarterly*, *25*(3). https://doi.org/10.2298/CICEQ180921002D

Edmunds, C. W., Molina, E. A. R., André, N., Hamilton, C., Park, S., Fasina, O., Adhikari, S., Kelley, S. S., Tumuluru, J. S., Rials, T. G., & Labbé, N. (2018). Blended feedstocks for thermochemical conversion: Biomass characterization and bio-oil production from switchgrass-pine residues blends. *Frontiers in Energy Research*, *6*(AUG). https://doi.org/10.3389/fenrg.2018.00079

Emadi, B., Iroba, K. L., & Tabil, L. G. (2017). Effect of polymer plastic binder on mechanical, storage and combustion characteristics of torrefied and pelletized herbaceous biomass. *Applied Energy*, *198*, 312–319. https://doi.org/10.1016/j.apenergy.2016.12.027

Emadi, B., Tabil, L. G., Li, X., & Mupondwa, E. (n.d.). *The Canadian Society for Bioengineering La Société Canadienne de Génie Agroalimentaire et de Bioingénierie Techno-economic feasibility of using recycled polymer plastic in torrefied and pelletized herbaceous biomass*.

EN15103. (2009). Solid Biofuels-Determination of Bulk Density. In *Landtechnik* (Vol. 60, Issue 3).

Fisher, E. M., Dupont, C., Darvell, L. I., Commandré, J. M., Saddawi, A., Jones, J. M., Grateau, M., Nocquet, T., & Salvador, S. (2012). Combustion and gasification characteristics of chars from raw and torrefied biomass. *Bioresource Technology*, *119*, 157–165. https://doi.org/10.1016/j.biortech.2012.05.109

Gao, W., Tabil, L. G., Dumonceaux, T., Espinel Ríos, S., & Zhao, R. (2017). Optimization of biological pretreatment to enhance the quality of wheat straw pellets. *Biomass and Bioenergy*, *97*. https://doi.org/10.1016/j.biombioe.2016.12.012

García, R., Gil, M. V., González-Vázquez, M. P., Rubiera, F., & Pevida, C. (2019). *Biomass Pelletization: Contribution to Renewable Power Generation Scenarios*. 269–294. https://doi.org/10.1007/978-981-13-3768-0_9

García, R., Gil, M. V., Rubiera, F., & Pevida, C. (2019). Pelletization of wood and alternative residual biomass blends for producing industrial quality pellets. *Fuel*, *251*(January), 739–753. https://doi.org/10.1016/j.fuel.2019.03.141

Garcia-Maraver, A. (2015a). *Biomass Pelletization Process* (pp. 53–66). https://doi.org/10.2495/978-1-84566-062-8/004

Garcia-Maraver, A. (2015b). *Factors Affecting Pellet Quality*. *85*, 21–35. https://doi.org/10.2495/978-1-84566-062-8/002

Garrido, M. A., Conesa, J. A., & Garcia, M. D. (2017). Characterization and production of fuel briquettes made from biomass and plastic wastes. *Energies*, *10*(7). https://doi.org/10.3390/en10070850

Ghiasi, B., Kumar, L., Furubayashi, T., Lim, C. J., Bi, X., Kim, C. S., & Sokhansanj, S. (2014). Densified biocoal from woodchips: Is it better to do torrefaction before or after densification? *Applied Energy*, *134*. https://doi.org/10.1016/j.apenergy.2014.07.076

Ghugare, S. B., Tiwary, S., & Tambe, S. S. (2017). Computational intelligence-based models for prediction of elemental composition of solid biomass fuels from proximate analysis. *International Journal of System Assurance Engineering and Management*, *8*. https://doi.org/10.1007/s13198-014-0324-4

Gilvari, H., de Jong, W., & Schott, D. L. (2019). Quality parameters relevant for densification of bio-materials: Measuring methods and affecting factors - A review. *Biomass and Bioenergy*, *120*(March 2018), 117–134. https://doi.org/10.1016/j.biombioe.2018.11.013

GLOBAL BIOENERGY STATISTICS 2022 World Bioenergy Association. (2022).

Graham, S., Eastwick, C., Snape, C., & Quick, W. (2017). Mechanical degradation of biomass wood pellets during long term stockpile storage. *Fuel Processing Technology*, *160*. https://doi.org/10.1016/j.fuproc.2017.02.017

Gummert, M., Van Hung, N., Chivenge, P., & Douthwaite, B. (2019). Sustainable Rice Straw Management. In *Sustainable Rice Straw Management*. https://doi.org/10.1007/978-3-030-32373-8

Haq, I. U., Qaisar, K., Nawaz, A., Akram, F., Mukhtar, H., Zohu, X., Xu, Y., Mumtaz, M. W., Rashid, U., Ghani, W. A. W. A. K., & Choong, T. S. Y. (2021). Advances in valorization of lignocellulosic biomass towards energy generation. *Catalysts*, *11*(3), 1–26. https://doi.org/10.3390/catal11030309

Hartley, I. D., & Wood, L. J. (2008). Hygroscopic properties of densified softwood pellets. *Biomass and Bioenergy*, *32*(1). https://doi.org/10.1016/j.biombioe.2007.06.009

Harun, N. Y., Parvez, A. M., & Afzal, M. T. (2018). Process and energy analysis of pelleting agricultural and woody biomass blends. *Sustainability (Switzerland)*, *10*(6). https://doi.org/10.3390/su10061770

Haykiri-Acma, H., & Yaman, S. (2022). Effects of torrefaction after pelleting (TAP) process on strength and fuel characteristics of binderless bio-pellets. *Biomass Conversion and Biorefinery*. https://doi.org/10.1007/s13399-022-02599-7

He, C., Tang, C., Li, C., Yuan, J., Tran, K. Q., Bach, Q. V., Qiu, R., & Yang, Y. (2018). Wet torrefaction of biomass for high quality solid fuel production: A review. *Renewable and Sustainable Energy Reviews*, *91*(March 2018), 259–271. https://doi.org/10.1016/j.rser.2018.03.097

Henriksen, U. B., Holm, J. K., Simonsen, P., Berg, M., Posselt, D., Nikolaisen, L., Plackett, D., & Møller, J. D. (2008). *Fundamental Understanding of Pelletization*. *June*.

Hosseinizand, H., Sokhansanj, S., & Lim, C. J. (2018). Co-pelletization of microalgae Chlorella vulgaris and pine sawdust to produce solid fuels. *Fuel Processing Technology*, *177*. https://doi.org/10.1016/j.fuproc.2018.04.015

Hu, H., Xie, N., Fang, D., & Zhang, X. (2018). The role of renewable energy consumption and commercial services trade in carbon dioxide reduction: Evidence from 25 developing countries. *Applied Energy*, *211*, 1229–1244. https://doi.org/10.1016/j.apenergy.2017.12.019

Huang, Y., Finell, M., Larsson, S., Wang, X., Zhang, J., Wei, R., & Liu, L. (2017a). Biofuel pellets made at low moisture content – Influence of water in the binding mechanism of densified biomass. *Biomass and Bioenergy*, *98*. https://doi.org/10.1016/j.biombioe.2017.01.002

Huang, Y., Finell, M., Larsson, S., Wang, X., Zhang, J., Wei, R., & Liu, L. (2017b). Biofuel pellets made at low moisture content – Influence of water in the binding mechanism of densified biomass. *Biomass and Bioenergy*, *98*, 8–14. https://doi.org/10.1016/j.biombioe.2017.01.002

Islas, J., Manzini, F., Masera, O., & Vargas, V. (2018). Solid biomass to heat and power. In *The Role of Bioenergy in the Emerging Bioeconomy: Resources, Technologies, Sustainability and Policy*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-813056-8.00004-2

J. A., J., A., T., & E. E., K. (2019). A Review of Pellet Production from Biomass Residues as Domestic Fuel. *International Journal of Environment, Agriculture and Biotechnology*, *4*(3), 835–842. https://doi.org/10.22161/ijeab/4.3.34

Jeguirim, M., Khiari, B., & Limousy, L. (2019). Biomass feedstocks. In *Char and Carbon Materials Derived from Biomass: Production, Characterization and Applications*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-814893-8.00001-8

Kaliyan, N., & Vance Morey, R. (2009). Factors affecting strength and durability of densified biomass products. In *Biomass and Bioenergy* (Vol. 33, Issue 3). https://doi.org/10.1016/j.biombioe.2008.08.005

Kiang, Y. H. (2018). Fuel Property Estimation and Combustion Process Characterization: Conventional Fuels, Biomass, Biocarbon, Waste Fuels, Refuse Derived Fuel, and Other Alternative Fuels. In *Fuel Property Estimation and Combustion Process Characterization: Conventional Fuels, Biomass, Biocarbon, Waste Fuels, Refuse Derived Fuel, and Other Alternative Fuels*.

Koondhar, M. A., Tan, Z., Alam, G. M., Khan, Z. A., Wang, L., & Kong, R. (2021). Bioenergy consumption, carbon emissions, and agricultural bioeconomic growth: A systematic approach to carbon neutrality in China. *Journal of Environmental Management*, *296*. https://doi.org/10.1016/j.jenvman.2021.113242

Krishnan, R., Hauchhum, L., Gupta, R., & Pattanayak, S. (2019). Prediction of Equations for Higher Heating Values of Biomass Using Proximate and Ultimate Analysis. *2nd International Conference on Energy, Power and Environment: Towards Smart Technology, ICEPE 2018*, *June*. https://doi.org/10.1109/EPETSG.2018.8658984

Kumar, L., Koukoulas, A. A., Mani, S., & Satyavolu, J. (2017). Integrating torrefaction in the wood pellet industry: A critical review. In *Energy and Fuels* (Vol. 31, Issue 1). https://doi.org/10.1021/acs.energyfuels.6b02803

Lehmann, B., Schröder, H. W., Wollenberg, R., & Repke, J. U. (2012). Effect of miscanthus addition and different grinding processes on the quality of wood pellets. *Biomass and Bioenergy*, *44*, 150–159. https://doi.org/10.1016/j.biombioe.2012.05.009

Liu, D., Teng, D., Zhu, Y., Wang, X., & Wang, H. (2023). Optimization of Process Parameters for Pellet Production from Corn Stalk Rinds Using Box–Behnken Design. *Energies*, *16*(12), 4796. https://doi.org/10.3390/en16124796

Liu, J., Jiang, X., Yuan, Y., Chen, H., Zhang, W., Cai, H., & Gao, F. (2022). Densification of Yak Manure Biofuel Pellets and Evaluation of Parameters: Effects on Properties. *Energies*, *15*(5), 1–14. https://doi.org/10.3390/en15051621

Ma, J., Feng, S., Shen, X., Zhang, Z., Wang, Z., Kong, W., Yuan, P., Shen, B., & Mu, L. (2021). Integration of the pelletization and combustion of biodried products derived from municipal organic wastes: The influences of compression temperature and pressure. *Energy*, *219*. https://doi.org/10.1016/j.energy.2020.119614

Manouchehrinejad, M., & Mani, S. (2018). Torrefaction after pelletization (TAP): Analysis of torrefied pellet quality and co-products. *Biomass and Bioenergy*, *118*. https://doi.org/10.1016/j.biombioe.2018.08.015

Moayedi, H., Osouli, A., Bui, D. T., Kok Foong, L., Nguyen, H., & Kalantar, B. (2019). Two novel neural-evolutionary predictive techniques of dragonfly algorithm (DA) and biogeography-based optimization (BBO) for landslide susceptibility analysis. *Geomatics, Natural Hazards and Risk*, *10*(1), 2429–2453. https://doi.org/10.1080/19475705.2019.1699608

Mohammadi, A., & Anukam, A. I. (2023). *Energy production features of Miscanthus pellets blended with Pine sawdust*. 1–19.

Mostafa, M. E., Hu, S., Wang, Y., Su, S., Hu, X., Elsayed, S. A., & Xiang, J. (2019). The significance of pelletization operating conditions: An analysis of physical and mechanical characteristics as well as energy consumption of biomass pellets. *Renewable and Sustainable Energy Reviews*, *105*(January), 332–348. https://doi.org/10.1016/j.rser.2019.01.053

Mostafa, M. E., Xu, J., Zhou, J., Chi, H., Hu, S., Wang, Y., Su, S., Elsayed, S. A., & Xiang, J. (2021a). Optimization and statistical analysis of the effect of main operation conditions on the physical characteristics of solid and hollow cylindrical pellets. *Biomass Conversion and Biorefinery*. https://doi.org/10.1007/s13399-021-01541-7

Mostafa, M. E., Xu, J., Zhou, J., Chi, H., Hu, S., Wang, Y., Su, S., Elsayed, S. A., & Xiang, J. (2021b). Optimization and statistical analysis of the effect of main operation conditions on the physical characteristics of solid and hollow cylindrical pellets. *Biomass Conversion and Biorefinery*. https://doi.org/10.1007/s13399-021-01541-7

Mukherjee, A., Okolie, J. A., Niu, C., & Dalai, A. K. (2022). Experimental and Modeling Studies of Torrefaction of Spent Coffee Grounds and Coffee Husk: Effects on Surface Chemistry and Carbon Dioxide Capture Performance. *ACS Omega*, *7*(1). https://doi.org/10.1021/acsomega.1c05270

Niedziółka, I., Szpryngiel, M., Kachel-Jakubowska, M., Kraszkiewicz, A., Zawiślak, K., Sobczak, P., & Nadulski, R. (2015). Assessment of the energetic and mechanical properties of pellets produced from agricultural biomass. *Renewable Energy*, *76*, 312–317. https://doi.org/10.1016/j.renene.2014.11.040

Nimmanterdwong, P., Chalermsinsuwan, B., & Piumsomboon, P. (2021). Prediction of lignocellulosic biomass structural components from ultimate/proximate analysis. *Energy*, *222*, 119945. https://doi.org/10.1016/j.energy.2021.119945

Nunes, L. J. R., Causer, T. P., & Ciolkosz, D. (2020). Biomass for energy: A review on supply chain management models. *Renewable and Sustainable Energy Reviews*, *120*(December 2019), 109658. https://doi.org/10.1016/j.rser.2019.109658

Nunes, L. J. R., Matias, J. C. O., & Catalão, J. P. S. (2014). A review on torrefied biomass pellets as a sustainable alternative to coal in power generation. *Renewable and Sustainable Energy Reviews*, *40*, 153–160. https://doi.org/10.1016/j.rser.2014.07.181

Pantaleo, A., Villarini, M., Colantoni, A., Carlini, M., Santoro, F., & Hamedani, S. R. (2020). Techno-economic modeling of biomass pellet routes: Feasibility in Italy. *Energies*, *13*(7), 1–15. https://doi.org/10.3390/en13071636

Park, S., Jeong, H. R., Shin, Y. A., Kim, S. J., Ju, Y. M., Oh, K. C., Cho, L. H., & Kim, D. (2021). Performance optimization of fuel pellets comprising pepper stem and coffee grounds through mixing ratios and torrefaction. *Energies*, *14*(15). https://doi.org/10.3390/en14154667

Park, S., Kim, S. J., Oh, K. C., Cho, L. H., & Kim, D. H. (2023). Developing a Proximate Component Prediction Model of Biomass Based on Element Analysis. *Energies*, *16*(1), 1–17. https://doi.org/10.3390/en16010509

Park, S., Kim, S. J., Oh, K. C., Cho, L., Kim, M. J., Jeong, I. S., Lee, C. G., & Kim, D. H. (2020). Investigation of agro-byproduct pellet properties and improvement in pellet quality through mixing. *Energy*, *190*. https://doi.org/10.1016/j.energy.2019.116380

Perea-Moreno, M. A., Samerón-Manzano, E., & Perea-Moreno, A. J. (2019). Biomass as renewable energy: Worldwide research trends. *Sustainability (Switzerland)*, *11*(3). https://doi.org/10.3390/su11030863

Perez-Jimenez, J. A. (2015). *Gaseous Emissions from the Combustion of Biomass Pellets*. https://doi.org/10.2495/978-1-84566-062-8/006

Picchio, R., Latterini, F., Venanzi, R., Stefanoni, W., Suardi, A., Tocci, D., & Pari, L. (2020a). Pellet production from woody and non-woody feedstocks: A review on biomass quality evaluation. *Energies*, *13*(11), 1–20. https://doi.org/10.3390/en13112937

Picchio, R., Latterini, F., Venanzi, R., Stefanoni, W., Suardi, A., Tocci, D., & Pari, L. (2020b). Pellet production from woody and non-woody feedstocks: A review on biomass quality evaluation. *Energies*, *13*(11), 1–20. https://doi.org/10.3390/en13112937

Popa, V. I. (2018). Biomass for Fuels and Biomaterials. In *Biomass as Renewable Raw Material to Obtain Bioproducts of High-Tech Value*. https://doi.org/10.1016/B978-0-444-63774-1.00001-6

Pradhan, P., Mahajani, S. M., & Arora, A. (2018a). Production and utilization of fuel pellets from biomass: A review. *Fuel Processing Technology*, *181*(September), 215–232. https://doi.org/10.1016/j.fuproc.2018.09.021

Pradhan, P., Mahajani, S. M., & Arora, A. (2018b). Production and utilization of fuel pellets from biomass: A review. *Fuel Processing Technology*, *181*(September), 215–232. https://doi.org/10.1016/j.fuproc.2018.09.021

Puig-Arnavat, M., Shang, L., Sárossy, Z., Ahrenfeldt, J., & Henriksen, U. B. (2016). From a single pellet press to a bench scale pellet mill - Pelletizing six different biomass feedstocks. *Fuel Processing Technology*, *142*, 27–33. https://doi.org/10.1016/j.fuproc.2015.09.022

Rahaman, S. A., & Salam, P. A. (2017). Characterization of cold densified rice straw briquettes and the potential use of sawdust as binder. *Fuel Processing Technology*, *158*, 9–19. https://doi.org/10.1016/j.fuproc.2016.12.008

Rajput, S. P., Jadhav, S. V., & Thorat, B. N. (2020). Methods to improve properties of fuel pellets obtained from different biomass sources: Effect of biomass blends and binders. *Fuel Processing Technology*, *199*(July 2019). https://doi.org/10.1016/j.fuproc.2019.106255

Ray, A. E., Li, C., Thompson, V. S., Daubaras, D. L., Nagle, N. J., & Hartley, D. S. (2017). Biomass Blending and Densification: Impacts on Feedstock Supply and Biochemical Conversion Performance. In *Biomass Volume Estimation and Valorization for Energy*. https://doi.org/10.5772/67207

Rezaei, H., Yazdanpanah, F., Lim, C. J., & Sokhansanj, S. (2020). Pelletization properties of refuse-derived fuel - Effects of particle size and moisture content. *Fuel Processing Technology*, *205*. https://doi.org/10.1016/j.fuproc.2020.106437

Riva, L., Nielsen, H. K., Skreiberg, Ø., Wang, L., Bartocci, P., Barbanera, M., Bidini, G., & Fantozzi, F. (2019). Analysis of optimal temperature, pressure and binder quantity for the production of biocarbon pellet to be used as a substitute for coke. *Applied Energy*, *256*. https://doi.org/10.1016/j.apenergy.2019.113933

Rozzi, E., Minuto, F. D., Lanzini, A., & Leone, P. (2020). Green synthetic fuels: Renewable routes for the conversion of non-fossil feedstocks into gaseous fuels and their end uses. *Energies*, *13*(2). https://doi.org/10.3390/en13020420

Ruan, R., Zhang, Y., Chen, P., Liu, S., Fan, L., Zhou, N., Ding, K., Peng, P., Addy, M., Cheng, Y., Anderson, E., Wang, Y., Liu, Y., Lei, H., & Li, B. (2019). Biofuels: Introduction. In *Biomass, Biofuels, Biochemicals: Biofuels: Alternative Feedstocks and Conversion Processes for the Production of Liquid and Gaseous Biofuels* (Issue x). https://doi.org/10.1016/B978-0-12-816856-1.00001-4

Said, N., Abdel Daiem, M. M., García-Maraver, A., & Zamorano, M. (2015). Influence of densification parameters on quality properties of rice straw pellets. *Fuel Processing Technology*, *138*. https://doi.org/10.1016/j.fuproc.2015.05.011

Sánchez, J., Curt, M. D., Robert, N., & Fernández, J. (2018). Biomass resources. In *The Role of Bioenergy in the Emerging Bioeconomy: Resources, Technologies, Sustainability and Policy*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-813056-8.00002-9

Sarker, T. R., Azargohar, R., Stobbs, J., Karunakaran, C., Meda, V., & Dalai, A. K. (2022). Complementary effects of torrefaction and pelletization for the production of fuel pellets from agricultural residues: A comparative study. *Industrial Crops and Products*, *181*. https://doi.org/10.1016/j.indcrop.2022.114740

Sarker, T. R., Nanda, S., Meda, V., & Dalai, A. K. (2023). Densification of waste biomass for manufacturing solid biofuel pellets: a review. In *Environmental Chemistry Letters* (Vol. 21, Issue 1). https://doi.org/10.1007/s10311-022-01510-0

Serrano, C., Monedero, E., & Portero, H. (2011). *Effect of moisture content, particle size and pine addition on quality parameters of barley straw pellets*. *January 2021*. https://doi.org/10.1016/j.fuproc.2010.11.031

Shang, L., Ahrenfeldt, J., Holm, J. K., Sanadi, A. R., Barsberg, S., Thomsen, T., Stelte, W., & Henriksen, U. B. (2012). Changes of chemical and mechanical behavior of torrefied wheat straw. *Biomass and Bioenergy*, *40*, 63–70. https://doi.org/10.1016/j.biombioe.2012.01.049

Shang, L., Nielsen, N. P. K., Dahl, J., Stelte, W., Ahrenfeldt, J., Holm, J. K., Thomsen, T., & Henriksen, U. B. (2012). Quality effects caused by torrefaction of pellets made from Scots pine. *Fuel Processing Technology*, *101*. https://doi.org/10.1016/j.fuproc.2012.03.013

Sharma, H. K., Xu, C., & Qin, W. (2019). Biological Pretreatment of Lignocellulosic Biomass for Biofuels and Bioproducts: An Overview. In *Waste and Biomass Valorization* (Vol. 10, Issue 2). https://doi.org/10.1007/s12649-017-0059-y

Sitek, T., Pospíšil, J., Poláčik, J., & Chýlek, R. (2021). Thermogravimetric analysis of solid biomass fuels and corresponding emission of fine particles. *Energy*, *237*. https://doi.org/10.1016/j.energy.2021.121609

Sivabalan, K., Hassan, S., Ya, H., & Pasupuleti, J. (2021). A review on the characteristic of biomass and classification of bioenergy through direct combustion and gasification as an alternative power supply. *Journal of Physics: Conference Series*, *1831*(1). https://doi.org/10.1088/1742-6596/1831/1/012033

Siyal, A. A., Liu, Y., Mao, X., Ali, B., Husaain, S., Dai, J., Zhang, T., Fu, J., & Liu, G. (2021). Characterization and quality analysis of wood pellets: effect of pelletization and torrefaction process variables on quality of pellets. *Biomass Conversion and Biorefinery*, *11*(5). https://doi.org/10.1007/s13399-020-01235-6

Song, B., Cooke-Willis, M., Theobald, B., & Hall, P. (2021). Producing a high heating value and weather resistant solid fuel via briquetting of blended wood residues and thermoplastics. *Fuel*, *283*.

https://doi.org/10.1016/j.fuel.2020.119263

Stasiak, M., Molenda, M., Bańda, M., Wiącek, J., Parafiniuk, P., & Gondek, E. (2017). Mechanical and combustion properties of sawdust—Straw pellets blended in different proportions. *Fuel Processing Technology*, *156*, 366–375. https://doi.org/10.1016/j.fuproc.2016.09.021

Thapa, S., & Engelken, R. (2020). Optimization of pelleting parameters for producing composite pellets using agricultural and agro-processing wastes by Taguchi-Grey relational analysis. *Carbon Resources Conversion*, *3*(May), 104–111. https://doi.org/10.1016/j.crcon.2020.05.001

Thapa, S., Mughal, M. A., Humphrey, K., & Engelken, R. (2018). Optimization of Process Parameters in the Pelletization of Crop Residues by Taguchi-Grey Relational Analysis. *International Journal of Agriculture, Environment and Bioresearch*, *3*(03).

Tumuluru, J. S. (2014). Effect of process variables on the density and durability of the pellets made from high moisture corn stover. *Biosystems Engineering*, *119*. https://doi.org/10.1016/j.biosystemseng.2013.11.012

Tumuluru, J. S. (2019). Pelleting of pine and switchgrass blends: Effect of process variables and blend ratio on the pellet quality and energy consumption. *Energies*, *12*(7). https://doi.org/10.3390/en12071198

Tumuluru, J. S., & Fillerup, E. (2020). Briquetting characteristics of woody and herbaceous biomass blends: Impact on physical properties, chemical composition, and calorific value. *Biofuels, Bioproducts and Biorefining*, *14*(5). https://doi.org/10.1002/bbb.2121

Tumuluru, J. S., Ghiasi, B., Soelberg, N. R., & Sokhansanj, S. (2021). Biomass Torrefaction Process, Product Properties, Reactor Types, and Moving Bed Reactor Design Concepts. *Frontiers in Energy Research*, *9*. https://doi.org/10.3389/fenrg.2021.728140

Tumuluru, J. S., Hess, J. R., Boardman, R. D., Wright, C. T., & Westover, T. L. (2012). Formulation, pretreatment, and densification options to improve biomass specifications for Co-firing high percentages with coal. In *Industrial Biotechnology* (Vol. 8, Issue 3). https://doi.org/10.1089/ind.2012.0004

Tumuluru, J. S., Wright, C. T., Hess, J. R., & Kenney, K. L. (2011). A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application. In *Biofuels, Bioproducts and Biorefining* (Vol. 5, Issue 6). https://doi.org/10.1002/bbb.324

Tursi, A. (2019). A review on biomass: Importance, chemistry, classification, and conversion. *Biofuel Research Journal*, *6*(2), 962–979. https://doi.org/10.18331/BRJ2019.6.2.3

Vaish, S., Sharma, N. K., & Kaur, G. (2022). A review on various types of densification/briquetting technologies of biomass residues. *IOP Conference Series: Materials Science and Engineering*, *1228*(1), 012019. https://doi.org/10.1088/1757-899x/1228/1/012019

Vinterbäck, J. (2004). Pellets 2002: The first world conference on pellets. *Biomass and Bioenergy*, *27*(6). https://doi.org/10.1016/j.biombioe.2004.05.005

Wang, L., Riva, L., Skreiberg, Ø., Khalil, R., Bartocci, P., Yang, Q., Yang, H., Wang, X., Chen, D., Rudolfsson, M., & Nielsen, H. K. (2020). Effect of torrefaction on properties of pellets produced from woody biomass. *Energy and Fuels*, *34*(12), 15343–15354. https://doi.org/10.1021/acs.energyfuels.0c02671

Wang, Y., Qin, R., Cheng, H., Liang, T., Zhang, K., Chai, N., Gao, J., Feng, Q., Hou, M., Liu, J., Liu, C., Zhang, W., Fang, Y., Huang, J., & Zhang, F. (2022). Can Machine Learning Algorithms Successfully Predict Grassland Aboveground Biomass? *Remote Sensing*, *14*(16). https://doi.org/10.3390/rs14163843

Williams, C. L., Emerson, R. M., & Tumuluru, J. S. (2017). Biomass Compositional Analysis for Conversion to Renewable Fuels and Chemicals. In *Biomass Volume Estimation and Valorization for Energy*. https://doi.org/10.5772/65777

Xing, J., Luo, K., Wang, H., & Fan, J. (2019). Estimating biomass major chemical constituents from ultimate analysis using a random forest model. *Bioresource Technology*, *288*. https://doi.org/10.1016/j.biortech.2019.121541

Xing, J., Luo, K., Wang, H., Gao, Z., & Fan, J. (2019). A comprehensive study on estimating higher heating value of biomass from proximate and ultimate analysis with machine learning approaches. *Energy*, *188*, 116077. https://doi.org/10.1016/j.energy.2019.116077

Zamorano, M., Popov, V., Rodríguez, M. L., & García-Maraver, A. (2011). A comparative study of quality properties of pelletized agricultural and forestry lopping residues. *Renewable Energy*, *36*(11).

https://doi.org/10.1016/j.renene.2011.03.020

Zhang, X., Gao, B., Zhao, S., Wu, P., Han, L., & Liu, X. (2020). Optimization of a “coal-like” pelletization technique based on the sustainable biomass fuel of hydrothermal carbonization of wheat straw. *Journal of Cleaner Production*, *242*. https://doi.org/10.1016/j.jclepro.2019.118426