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BIOENERGY CONVERSION TECHNOLOGIES: A REVIEW AND CASE STUDY
TEHNOLOGIJE KONVERZIJE BIOENERGIJE: PREGLED I STUDIJA SLUČAJA

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APSTRAKT

Pretvaranje organskog otpada i energetskih useva u gorivo pomoglo bi društvu proizvodnjom čistog goriva iz obnovljivih sirovina. Industrijska biogoriva mogu biti nezagađujuća i održiva ako su pravilno povezana sa prirodnim ekološkim ciklusima. Uobičajeni metod proizvodnje toplote i energije iz bioenergetskih izvora je gasifikacija biomase. Štaviše, piroliza i hidrotermalna karbonizacija su obećavajući termohemijski procesi za pretvaranje biomase u tečna goriva i hemijska jedinjenja. Anaerobna digestija je još jedan dobro uspostavljen metod koji uspešno transformiše organske otpadne materije u biogas. Svrha studije je da se pregledaju trenutne tehnologije konverzije bioenergije i da se obezbede kvantitativni podaci i interpretacija toplotne vrednosti, približne i elementarne analize i prinosa proizvoda specifičnih za dobijanje bioenergije iz nekih odabranih materijala biomase kao što su otpad od prerade maslina i stabljike pamuka. Štaviše, neki proizvodi iz konverzije (npr. biougalj iz pirolize) mogu se koristiti kao poboljšivač kvaliteta zemljišta za obnavljanje hranljivih materija i ugljenika u zemljištu. Ovo poslednje može dodatno da služi kao unapređenje skladišne moći vode. Stoga, korišćenje biomase ima potencijal da bude značajan izvor energije i prilika za smanjenje ekoloških problema i finansijskih troškova. Ova studija doprinosi potrebnom razumevanju energije dobijene iz toplotnih i bioloških proizvoda konverzije biomase. U tom kontekstu, u skladu sa karakteristikama različitih vrsta biomase, treba primeniti odgovarajuće metode korišćenja za proizvodnju bioenergije kako bi se ostvarile ekološke, ekonomske i energetske koristi. Studija je zaključena nekim komentarima o budućem potencijalu ovih procesa.

Ključne reči: *biomasa, bioenergetske tehnologije, biogoriva.*

ABSTRACT

The conversion of organic waste and energy crops into fuel would help society by producing clean fuel from the regenerative feedstock. Industrial biofuels may be non-polluting and sustainable if properly linked with natural ecological cycles. A common method of producing heat and power from bioenergy is biomass gasification. Furthermore, pyrolysis and hydrothermal carbonization are promising thermochemical processes for converting biomass into liquefied fuels and chemicals. Anaerobic digestion is another well-established method that successfully transforms organic waste matter into biogas. The purpose of the study is to review current bio-energy conversion technologies and to provide quantitative data and interpretation of the heating value, proximate and elemental analysis, and product yields specific to bioenergy recovery from some selected biomass materials such as olive mill waste and cotton stalks. Moreover, some products from the conversion (e.g. biochar from pyrolysis) can be used as a soil additive to recover nutrients and carbon in the soil. The latter can additionally act as water storage. Therefore, utilizing biomass has the potential to be a significant source of energy and an opportunity to reduce environmental issues and financial costs. This study contributes to the needed understanding of energy derived from thermal and biological conversion products of biomass. In this context, according to the characteristics of different kinds of biomass, appropriate utilization methods should be applied to produce bioenergy to realize environmental, economic and energy benefits. The study concluded with some comments on the future potential of these processes.

Keywords: *Biomass, bioenergy technologies, biofuels.*

INTRODUCTION

Increased atmospheric concentrations of greenhouse gases (GHGs), mainly methane and nitrous oxide from agriculture manure management and carbon dioxide (CO2) from the burning of fossil fuels, are believed to be raising average global temperatures (Bui et al., 2018). According to the International Energy Agency, GHGs are expected to rise by 70% and 60%, respectively, between 2011 and 2050 (*Key World Energy Statistics 2020 – Analysis - IEA*, n.d.). The sustainable production of biomass fuels "so that it is just recycling atmospheric CO2 and is, therefore, C-neutral " is in line with the UN thematic focus on climate protection, as biomass fuels can play an important role in reducing the need for GHG and acid rain emitting fossil fuels(Tripathi et al., 2016). The second impact contributes to the Sustainable Development Goals (SDGs 7) providing Affordable and Clean Energy. In this context, it's worth mentioning that the annual world production of biomass is estimated at 146 billion tons a year (energy equivalent to 788 EJ and this is 1.2 times larger than the world energy consumption of 642EJ, However, the contribution of biomass to the global energy demand is only 10 % (*Dunnigan, Ashman, et al., 2018*) (*Obour et al., 2018*), and in the most regions, the use of biomass still needs to become sustainable, this being true both where traditional and modern technologies are applied. By 2035, biofuels could realistically provide at least a quarter of the estimated world's total primary energy supply *(Al Afif, Pfeifer, et al., 2020*). In order to increase the amount of renewable bioenergy in the total primary energy supply, innovative feedstocks or inputs are needed. However, utilizing edible biomass for biofuel production raises a number of environmental and social concerns, including those related to land usage, food competition, and lifecycle (*Biomass with CO2 Capture and Storage (Bio-CCS)*, n.d.). To overcome some of these difficulties, biofuels can be produced from various types of feedstocks, such as non-edible lignocellulosic biomass, various residues, and waste products like bio-waste and municipal solid waste (*Dou et al., 2019; R. A. Lee & Lavoie, 2013*). Although many of agricultural wastes are frequently produced, they have little to no value(Dunnigan, Ashman, et al., 2018; Obour et al., 2018). For example, it is estimated that 50 million tons of cotton biomass waste are produced annually (*Bioenergy from Cotton Industry Wastes: A Review and Potential : University of Southern Queensland Repository*, n.d.). Some crops generate even greater amounts of waste, such as the wastewater from olive mills, which accounts for between 10 and 30 million m3 per year without any significant end-of-use application (Dunnigan, Morton, et al., 2018).

In addition, biowaste can be hazardous to the ecosystem. For instance, cotton waste that was left over after harvest can carry pests that are harmful to crops ("Invasive Species Compendium," n.d.). The most common method to prevent pest infestation in countries without effective pest management tactics is to burn the leftovers in the field, or more labor- and time-intensive, to shred and shovel residues into the soil to a depth of 6 inches (*Hamawand et al., 2016*).

In the same context, olive mills in olive oil- producing countries produce a huge amount of waste that needs sustainable management(*Al Afif & Linke, 2019*), as the traditional disposal of it through discharging wastewater into river streams or tailing ponds can damage the ecosystem and have a negative impact on the survival of species. Recent studies on energy recovery from agricultural waste (*Al Afif et al., n.d.; Al Afif, Pfeifer, et al., 2020; Al Afif, Wendland, et al., 2020; Al Afif & Pfeifer, 2021; Schaffer et al., 2019*) address the problems resulting from traditional waste handling.

Although the anaerobic digestion of biomass could foster a circular economy and boost the concentration of soil organic carbon, by breaking down organic waste for producing sustainable energy (*Hmid et al., 2014*), applying biogas sludge to arable land for providing vital nutrients like nitrogen and phosphorus to agricultural output, there are several challenges facing increasing the anaerobic digestion turnover *(Nasir et al., 2012*).

Also, in this context, previous research confirmed that converting these wastes to energy using various thermochemical conversions such as gasification, pyrolysis and hydro-carbonization, will minimize the land required for processing, and the energy produced may offset the much higher capital costs involved. However, the application of these techniques is still limited and needs more understanding of the nature of these conversions.

The purpose of the study is to review current bioenergy conversion technologies and to provide quantitative data and interpretation of the heating value, the strengths, weaknesses and the opportunities of different options for utilizing agricultural wastes with focusing on cotton stalk (CS) and olive mill waste (OMW) as a case study.

RESULTS AND DISCUSSION

Bioenergy conversion technologies

Replacement of fossil fuels with bio-based alternatives is one way to address energy sustainability. Heat and electrical power, needed worldwide, can also be produced through bioconversion technologies. The bioenergy carriers are solid, liquid, or gaseous fuels that can be produced from existing technologies. Although liquid fuels are frequently employed in motor vehicles, they can also be used in stationary engines or turbines. Solid fuels are directly burned to produce heat, power, or combined heat and power (CHP). While gaseous fuels can be used for a full range of end-uses.

There are three fundamental biomass conversion pathways to convert raw biomass into useful energy: Bio-chemical, thermo-chemical and physical-chemical. The broad categories of biomass energy conversion processes are shown in Fig. 1.

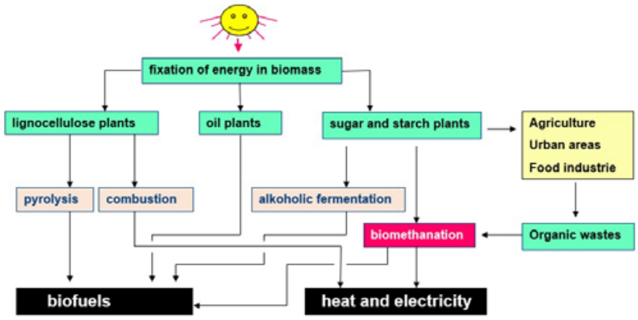

Fig. 1. Process schematic diagram for biomass energy conversion

Bio-chemical conversion refers the use of specific microbes or enzymes to generate valuable products, and encompasses two primary process options: anaerobic digestion to biogas, and fermentation to ethanol using the by-product and organic wastes from sugar and starch plants. Thermo-chemical conversion routes occur at elevated temperature (and sometimes pressure) for conversion. The four main process options presented here are combustion, hydrothermal processing, pyrolysis, gasification. Physio-chemical conversion is the use of chemicals or catalysts for conversion at ambient or slightly elevated temperatures. It consists principally of extraction (with esterification) where oilseeds are crushed to extract oil.

Biochemical conversion

Using yeast and/or specific bacteria yeast to transform waste or biomass into usable energy is referred to as biochemical conversion (*S. Y. Lee et al., 2019*). For the purpose of fractionating the various cell wall components, a pretreatment step is necessary due to the refractory character of lignin and its binding with holocellulose. Pretreatment is one of the main financial outlays in the biochemical conversion process *(Alvira et al., 2010*). Since it exposes the cellulose surface to enzyme attack, enhances enzymatic digestibility, and speeds up subsequent processes it is a vital step affecting the overall process (*Al Afif, Pfeifer, et al., 2020*). There is a number of pretreatment techniques applied. The Fig. 2 gives an overview of the available options of Biomass pretreatment techniques for biogas production, its worth noting that these pretreatment options are also valid for other biochemical conversions such as alcoholic fermentation and bioethanol production.

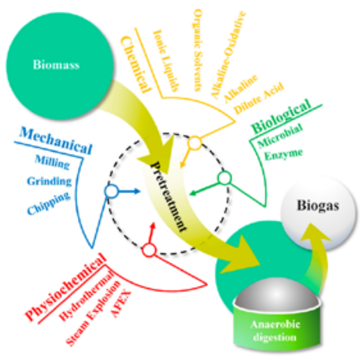

Fig.2 Biomass pretreatment techniques (Hernández-Beltrán et al., 2019)

Alcoholic fermentation

Bioethanol can be obtained via alcoholic fermentation of biomass residues containing fermentable sugars that are converted from cellulose and hemicellulose components of biomass in the existence of yeast or bacteria. As the microbes have difficulty metabolizing the polysaccharides found in the biomass, hydrolysis is carried out to break down the polysaccharides into simple sugars before feeding *(S. Y. Lee et al., 2019*). The most popular hydrolysis processes make use of enzymes, acid, and alkali. Although acid treatment is quick and inexpensive, the environment's acidity may cause sugars to change into unfavorable forms. Enzymatic treatment, in contrast, is effective and does not produce unwanted byproducts, although enzymes are more expensive, and the process is slower. For agricultural residues and herbaceous crops like cotton, alkaline pretreatment is often found to be more effective (*Silverstein et al., 2007)*.

Cotton stalks offer a lot of potential as a bioethanol feedstock, according to Christopher et al. *(Christopher et al., 2017*), who found that cellulase combined with betaglucosidase was able to hydrolyze alkali-treated biomass with an efficiency of 80%.

Before hydrolysis, cell disruption techniques can be used to boost its effectiveness and cut down on its duration*(Günerken et al., 2015*). Distillation must be used to concentrate the resulting crude alcohol (10–15% ethanol) (*Bibi et al., 2017*). Liquefaction, gasification, or microwave-assisted pyrolysis are still viable options for turning the residual solid waste into useful products.

Concerning OMW which is a semi-solid waste with high concentrations of lignin and cellulose, both recalcitrant substances that need to be hydrolyzed, through anaerobic processes, to degrade them into ethanol. On another hand, OMW has a high content of polyphenols, which inhibit microbial metabolism and, consequently, the conversion of the substrates into ethanol. Therefore, different pretreatments need to improve the bioethanol produced from OMW *(Battista et al., 2016; Nait M'Barek et al., 2020*).

Anaerobic digestion

In anaerobic digestion, organic material is hydrolyzed into sugars, amino acids, and fatty acids under oxygen-free conditions *(S. Y. Lee et al., 2019*). The hydrolytic products then undergo fermentation and methanogenesis, producing biogas that is mainly composed of methane (50-60%) and carbon-dioxide (*Al Afif, Pfeifer, et al., 2020; Cantrell et al., 2008*). Anaerobic digestion can accommodate wet biomass with moisture content up to 90%(*Brennan & Owende, 2010*).

Isci and Demirer (Isci & Demirer, 2007) found that cotton wastes can yield 65-86 lN CH_4 kg^{-1} VS $(24\ days)^{-1}$ when digested anaerobically. Al Afif et al. (Al Afif, Wendland, et al., 2020) investigated using organosolv plus supercritical carbon dioxide pretreatment of cotton stalks for methane production. The pretreatment increased the methane yield up to 20% compared with untreated samples. The highest methane yield of 177 lN kg^{-1} VS was achieved by pre-treatment with organosolv plus SC-CO_2 at 100 bar and 180°C for 140 minutes. Biogas quality increased with pretreatment from 50 to 60%.

The study by Al Afif and Pfeifer found that using three-phase olive mill solid waste (3POMSW) as a mono-substrate for biogas production is effective. Temperature significantly affects the biogas and methane yield during anaerobic digestion of 3POMSW. Thermophilic processing results in a 10% increase in methane yield and a 17.2% increase in biogas yield compared to mesophilic conditions. Therefore, it was concluded that thermophilic conditions are more successful in completing the anaerobic digestion of 3POMSW. The optimal enzyme mixture was found to be Metha Plus and Hemicellulase, which resulted in a 1.3% increase in methane yield. This could potentially reduce the cost of biogas upgrading and offset the cost of added enzymes. However, further studies are needed to determine the optimal concentration, selection, and mixture of enzymes, as this has significant economic implications (*Afif & Pfeifer, 2022*). Al Afif and Linke found that anaerobic digestion of 3POMSW in continuously stirred tank reactor was most efficient during the first 10 weeks under mesophilic and thermophilic conditions. Increasing the organic loading load (OLR) did not harm bio-methanation. Adding enzymes resulted in higher biogas yields and improved process stability, especially under thermophilic conditions. However, all experiments showed initial signs of reactor failure after 70 days (*Al Afif & Linke, 201*9). To ensure the sustainability of the procedure, a preventative measure should be implemented. To do this, it is necessary to look into the phenol content during the anaerobic digestion of 3POMSW under various hydraulic retention times (HRTs) and OLRs. Additionally, it is advised to investigate the techno-economic viability of the following alternative processes: the extraction of phenols from 3POMSW prior to anaerobic digestion; the use of "an intermittent operation which consists of an interruption of the reactor feeding during a certain amount of time (feedless or stabilization period), in order to allow for a more thorough biological breakdown of the substrates accumulated in the sludge bed during the feed period (*Chan et al., 2018*).

Further research into the technical challenges of the suggested management system at the pilot- and demo levels is strongly recommended.

Methods of optimization of the biogas production process- case study

The University of Natural Resources and Life Sciences, BOKU, Vienna is involved in bioenergy research. The methodology employed in their institutes is pictured in Fig.3. Starting from a selected biomass feedstock, measurements such as proximate and ultimate analysis and calorific value are performed according to standards (D05 Committee, n.d.; D07 Committee, n.d.; E48 Committee, n.d.).

Based on the results of the analyses, we could be sure that, the C/N ratio of feedstocks lies between 20 and 40, thus in a range that does not influence methanogens by toxic levels of ammonia (*Al Afif & Amon, 2019*). Furthermore, the Higher heating value (HHV) and Lower heating value (LHV) values of the raw materials and of each sample could be calculated based on the elemental analysis. followed by theoretical biogas yield calculations. Secondly, the anaerobic digestion batch trials are carried out in triplicate in accordance with VDI 4630(*VDI 4630 - Fermentation of organic materials - Characterization of the substrate, sampling, collection of material data, fermentation tests*, 2016). Results obtained from biogas production measurements via audiometer technique are used to model and evaluate the process, then, EcoGas (Version 07-E1) Software usually used for the simulation, dimensioning and to perform the economic analysis of the case study biogas plant for treatment of by-products from biomass. It's worth knowing that EcoGas software has been developed at BOKU-Vienna- is part of a comprehensive and inclusive toolkit comprising technological, economical, social, environmental and cultural dimensions of development. Where the techno-economic feasibility study is an important step towards scaling-up the biogas plant.

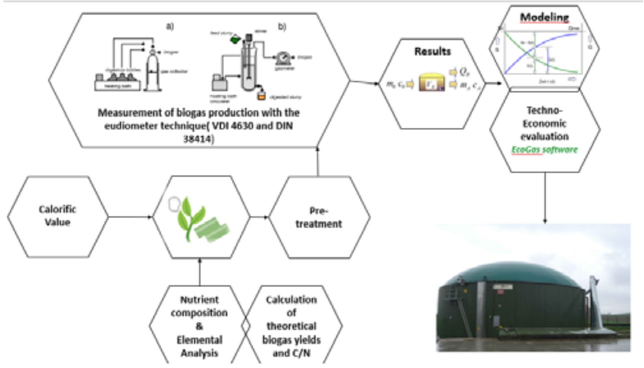

Fig.3. Biomass to biogas plant method

Thermochemical conversion

The selection of thermochemical conversion type can be influenced by the nature and quantity of biomass feedstock, the preferred type of energy, for example, end use conditions, environmental principles, financial circumstances and project precise aspects (*Goyal et al., 2008*). Based on several research studies, it was reported that thermal conversion technologies have gained extra attention due to the availability of industrial infrastructure to supply thermochemical transformation equipment that is highly developed, short processing time, reduced water usage and added advantage of producing energy from plastics wastes which cannot be digested by microbial activity (*Uzoejinwa et al., 2018*). Additionally, thermochemical conversion is essentially independent of environmental circumstances for production purposes. Therefore, conversion techniques will be covered individually.

Hydrothermal conversion

Biomass is converted to an energy-dense product via hydrothermal processes. No pre-drying of the feedstock is required because the technique operates in an aqueous environment, allowing for the direct use of biomass with greater moisture contents(*Nanda et al., 2013*). Solid fuel (hydrochar) is produced via hydrothermal carbonization at temperatures between 180 and 280 °C (*Balat, 2011*). Hydrothermal liquifaction, which produces bio-crude or crude-oil, a liquid fuel made up of insoluble organics, occurs between 250 and 375°C and at a pressure of 10 to 25 MPa *(Ayala-Cortés et al., 2021; Sukumaran et al., 2010*). Bio-crude needs little processing before it can be utilized commercially, while liquifaction byproducts have profitable applications (i.e. fertilizer). Furthermore, during the hydrothermal gasification (HTG) process, which involves heating biomass to high temperatures above 375°C, macromolecules are broken down into molecules with lower molecular weights, producing syngas. Therefore, the distribution of products and nutrients between the solid, liquid, and gaseous phase can be adjusted via the process conditions (pressure, temperature, residence time, heating rate, pH, additives, catalysts, etc.) (*Al Afif, Pfeifer, et al., 2020*).

Hydrothermal carbonization depletes compounds rich in oxygen and hydrogen and thereby increases the carbon content in the hydrochar compared to the starting material. Due to the increased carbon content of the hydrochar, the heating value increases. The change in elemental composition affects O/C and H/C ratios. Van Krevelen diagram allows for an accurate comparison of hydrochar to the raw feedstock as well as to fossil fuels conventionally used as energy sources. The results from Seyedsadr et al.(*Seyedsadr et al., 2018*) are shown on the Fig. 4. It is visible that all hydrochar samples have better fuel characteristics compared to the initial feedstock. The HTC process temperature of 200°C and 360 minutes residence time yields hydrochars with properties comparable to peat.

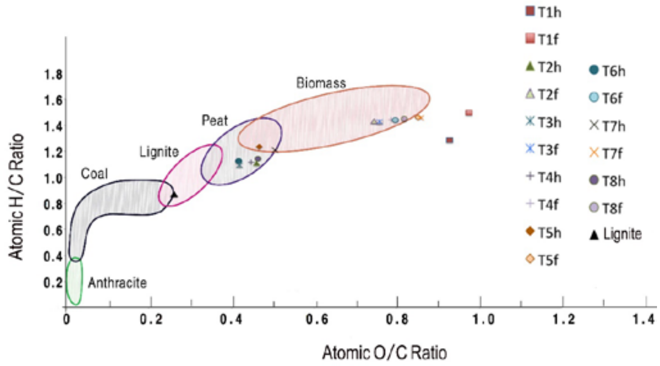

Fig. 4. Van Krevelen diagram for the hydro-chars produced from agricultural residues and sludge from a biogas plant (Seyedsadr et al., 2018).

The hydrothermal carbonization of CS kills the eggs of the pink bollworm and other pathogens. There is still a need for research in the area of reduction of impurities and in the accumulation of nutrients in the coal. (*Seyedsadr et al.,2018*) investigate the use of HTC in the production of hydrochar from CS. They concluded that hydrothermal carbonization is a promising conversion technology to provide bioenergy from CS. And there was a strong dependence between the residence time and the char quality, as the LHV of the hydrochar from CS increased with increasing residence time, whereas the total amount of hydrochar was decreased (*University of Natural Resources and Life Sciences, Vienna (BOKU) - Research Portal*, n.d.).

The study by Gimenez et al. suggested optimal conditions for HHV to be 240°C, 6h, and S:L of 0.3 g ml^{-1}. They have also found significant increases in HHV and carbon concentration compared to raw olive mill waste. The physicochemical properties of the hydrochars suggest potential applications as adsorbent material or precursor of activated carbon (*Gimenez et al., 2020)*.

Future research might focus on setting up a facility that can handle both wet and dry feedstock, studying the impact of different factors, improving conversion, and creating theoretical models that appropriately depict the process depending on the feedstock (*Gollakota et al., 2018*).

Pyrolysis

Pyrolysis and gasification are two of the thermochemical biomass conversion methods that are frequently researched. Pyrolysis is the thermal degradation of biomass, occurring in an oxygen-free environment at temperatures that can reach as high as 700 °C. Organic materials are broken down into solid, liquid, and gas mixtures during the pyrolysis process. The ability of gasification to produce fuel gas that can be burned to produce heat distinguishes it from pyrolysis. Yet, the pyrolysis process yields a liquid fuel known as pyrolysis oil or bio-oil that can replace fuel oil in the production of electricity or for the application of static heating. The ability of the resulting bio-oil to be easily transported and simply stored makes liquid fuel produced by pyrolysis superior to fuel gas produced by gasification *(Dhyani & Bhaskar, 2018*). The three types of pyrolysis processes—slow, rapid, and flash pyrolysis—differ depending on how they operate. The operational circumstances have an impact on the makeup of their products. The decomposition process used in slow pyrolysis results in char at low temperatures, slow heating rates, and lengthy vapour residence times. The main product of fast pyrolysis is bio-oil, which occurs at a controlled temperature of about 500 °C, a short residence time of less than two seconds, and a high heating rate of more than 200 °C per second.

In contrast, flash pyrolysis has a much faster heating rate than fast pyrolysis and a far shorter reaction time. Currently, the liquid output from quick pyrolysis is receiving greater focus. This is a result of the benefits of pyrolysis oil, which has a high yield of up to 75 weight percent, and of cost-effective, energy-efficient, and ecologically friendly technology *(Bridgwater, 2012; Jahirul et al., 2012*). Pyrolysis oil is a viscous substance that is dark brown in color. It has a variety of chemical compositions, including acids, alcohols, aldehydes, phenols, and oligomers that originated from lignin, and it has a low calorific value (*Rahman et al., 2018*). Recent years have seen a significant increase in the properties of pyrolysis oil.

It is necessary to improve pyrolysis oil so that it can be used in place of crude oil. Pyrolysis oil upgrading can be done in a number of ways, including by physical, chemical, and catalytic methods. Notwithstanding the significant success of recent engineering efforts on this subject (*Al Afif et al., n.d.*), more research on innovative reactors with increased cost and overall efficacy should be conducted.

Al Afif et al. studied pyrolysis of cotton stalks. Rotary kiln pyrolysis avoids ash melting issues and provides the volatile product fraction as fuel for high temperature applications. The pyrochar produced can be used for soil amadment with great stability. Molar ratio of O/C < 0.1 shows half-lives in soil could be in the order of millennia. The direct negative emissions reached through pyrolysis of cotton stalks in combination with soil-storage of pyrolysis char amount to 2.42t of CO_2 per hectare and year (*Al Afif et al., n.d.*).

Little work was done with pyrolysis of olive mill waste. Due to higher moisture content, the pre-drying is required. However, the studies by (Morvová et al., 2019; Piscitelli et al., 2023) obtained promising results, producing quality hydrochar with properties comparable to coal. The future research should focus on introducing pyrolysis of 3POMSW into an integrated system.

Gasification

Gasification is the thermochemical conversion of biomass into syngas, a chemical or fuel, by partial oxidation and reformation with steam, carbon dioxide, or other gasification agents. Less oxygen is present in the biomass than during combustion. The heat needed for endothermal processing is produced by the ex or in situ combuction of char or gas since gasification can be allo- or autothermal (*Salatino, 2016*). One of the most effective ways to transform the chemical energy contained in biomass into heat and other useful kinds of energy is gasification. The range of estimates for overall exergetic efficiency is between 80.5 and 87.6% *(Puig-Arnavat et al., 2010*).

It is closely connected to pyrolysis since both involve the devolatilization of biomass in the absence of oxygen or air to produce energy-efficient byproducts without complete combustion. However, through initial oxidation and subsequent reduction, the procedure is optimized for maximal gas yield (Boyle & Open University, 2012; Puig-Arnavat et al., 2010). The average processing temperature for gasification is between 750 and 900 °C for fixed and fluidized beds, between 1200 and 1500 °C for entrained flow, and up to 3000 °C for plasma applications. The gases carbon monoxide, carbon dioxide, methane, water, hydrogen, gaseous hydrocarbons, little char residue, and condensed oil and tar make up a large component of the products produced by gasification.

In order to obtain the desired result, syngas, an oxidizing agent is given to the process in the form of atmosphere or steam. The gaseous tar or oil in the gas is then condensed. The gas may not have enough energy to operate autothermally. Heating values of 12–14 MJ/m^3 are attained for allothermal operation. A char residue is left behind due to the process' comparatively low temperature; this residue can later be gasified by burning it at a high temperature, such as at 1000°C, while also adding steam to the process(Al Afif, Pfeifer, et al., 2020).

As a result, the steam is broken down into oxygen and hydrogen, which combine with the carbon in the char to form CO and H_2. After impurities including hydrogen sulfide, ammonia, and tar have been eliminated, high-quality syngas can be produced from the CO and H_2 yield of the process by employing oxygen rather than air. By the Fischer-Tropsch process, this syngas has the capacity to be converted into methanol, a valuable liquid fuel, as well as other kinds of hydrocarbon molecules. From 40% in simple designs to around 75% in processes with good designs, the efficiency of the total process varies (Boyle & Open University, 2012). According to Allesina et al., gasification of cotton residue serves as the foundation for regional circular economy models (Allesina et al., 2018).

Integrated system

Thermochemical and biochemical processes can be effectively combined. The study by Monlau et al. explored the feasibility of a hybrid system that combines anaerobic digestion and pyrolysis to increase energy recovery from agricultural residues and improve the sustainability of the anaerobic digestion plant. Physico-chemical characteristics of the solid digestate were determined. Pyrolysis experiments were conducted at different temperatures (400, 500, and 600°C) and the resulting syngas and bio-oil were characterized. A preliminary energy balance was created to assess the sustainability of coupling anaerobic digestion and pyrolysis processes. Fig. 5 illustrates the study's symbiotic concept (Monlau et al., 2015).

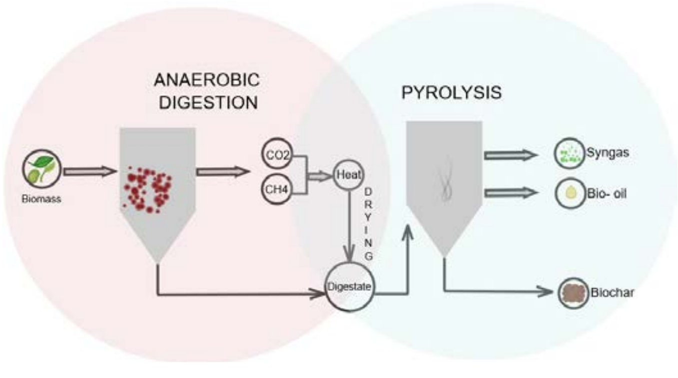

Fig 5. Integrated energy system adapted from the study by Monlau et al (Monlau et al., 2015).

Results showed that heat from anaerobic digestion could be used for drying the solid digestate, while pyrolysis produced syngas, oil, and char. The hybrid system increased electricity production by 42% compared to an anaerobic digestion stand-alone plant. This proposed hybrid dual system shows promise for increasing energy recovery from agricultural residues and enhancing the sustainability of anaerobic digestion. However, before any commercial application, a pilot-scale implementation is necessary to verify the beneficial properties of char as soil amendment.

Bioenergy generation integrated renewable energy systems

In comparison to single resource-based energy generation systems, integrated renewable energy systems can increase energy storage capacity, reduce energy production costs, improve the quality of generated power, and increase the overall energy conversion efficiency of power generation. Furthermore, such systems offer greater flexibility and promote overall socio-economic growth (*Al Afif et al., 2023; Chauhan & Saini, 2016*).

Understanding the possible configurations of bioconversion of biomass processing technologies (gasification, pyrolysis, hydrothermal gasification, hydrothermal carbonization, bio methanation or alcoholic fermentation) integrated with renewable energy technologies (solar thermal, fuel cell, fusion power, or energy storage, wind) is crucial for further development and propagation of the integrated renewable energy system.

Recently, rapid development has been seen in the integration of other green energy technologies with biomass processing for bioenergy (*Al Afif et al., 2023; Al-Najjar, El-Khozondar, et al., 2022; Al-Najjar et al., 2020; Al-Najjar, Pfeifer, et al., 2022; J. Lee, Lin, et al., 2023*). For sustainable and practical power production that will result in greater environmental benefits, it is still crucial to choose properly integrated renewable energy system configurations.

For instance, Facchinetti et al. worked on the integration of a solid fuel cell-gas turbine cycle powered with hydrothermally converted biomass obtaining the efficiency of 63% *(Facchinetti et al., 2012*). Heidari et al. performed hydrothermal carbonization of biomass. The hydrochar was used in the integrated system to produce power and process water in anaerobic digestion to obtain biogas later used as a gaseous fuel (*Heidari et al., 2020*). On the other hand, biomass can be anaerobically digested to produce biogas that can be used to generate heat or electricity, while the digestate can be pyrolyzed in the integrated system to obtain gas, oil, and char. Deng at al. found that such a system could be self-sustaining by combusting pyrolytic gas and excess char. Another important aspect is the energy storage (*Deng et al., 2020*). Concepts such as Green to Green energy system aim to find a green storage system, such as fuel cell, for the green energy*(Haddad et al., 2022; Ramadan, 2021*). Lin et al. proposed a plant for simultaneous generation of electricity and liquid hydrogen involving a lignocellulosic biomass gasification-integrated gas turbine and hydrogen liquefaction cycle with an electrolyzer process *(Lin et al., 2022*).

Figure 6 shows an example of an integrated renewable energy system. Biomass is used in the process of anaerobic digestion to generate digestate and biogas. The gas is combusted, and the digestate is dried and used as a feedstock in the pyrolyser. The digestate from the pyrolyser is separated into bio-oil and biochar, which are both products that can be used independently. Syngas, as well as photovoltaics and wind power, are used to generate energy. The energy is controlled and stored in the battery system before being supplied to the consumer.

However, study by Lee at al. showed that more research should be done on testing conceptually created models in real life conditions, addressing power fluctuation issues in the grid-connected system, removal of ash and moisture via pre-treatment technologies, etc. (*J. Lee, Kim, et al., 2023*).

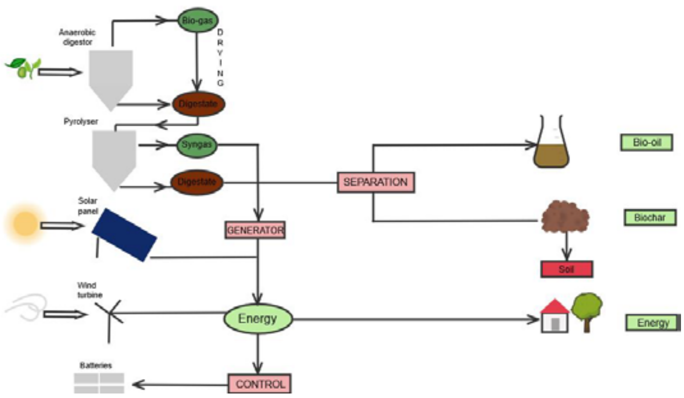

Fig. 6. The layout of a model integrated renewable energy system.

CONCLUSION

In this review, the current technological developments in the bioenergy conversion of biomass and the integrated renewable energy systems for the generation of biopower were summarized and discussed with the respective economic and environmental aspects of the systems, the strengths, weaknesses and the opportunities of different options for utilizing agricultural wastes with focusing on cotton stalk (CS) and olive mill waste (OMW) as a case study. Analyzing the existing literature critically may prompt some study questions. Therefore, ongoing efforts should be made to increase the integrated system's viability and efficacy in the future. It covers specific techniques, including anaerobic digestion, hydrothermal conversion, pyrolysis, gasification, and alcoholic fermentation. We highlight the need for innovative feedstocks and inputs to increase the amount of renewable bioenergy in the total primary energy supply. Good practice examples were mentioned such as the University of Natural Resources and Life Sciences and their research on biogas, successful integrated biomass conversion system, as well as the current position in integrated renewable energy systems. However, more research should be done on testing conceptually created models in real life conditions, addressing underlying issues such as power fluctuation issues in the grid-connected system and removal of ash and moisture via pre-treatment technologies in the renewable energy systems.

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