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Renewable Resources and Biorefineries

Edited by Eduardo Jacob-Lopes
and Leila Queiroz Zepka

RENEWABLE RESOURCES AND BIOREFINERIES

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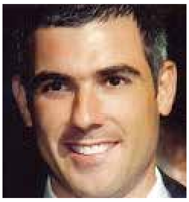
Meet the editors



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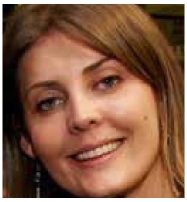

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Contents

Preface

Will fossil resources continue to lead the way for the industrial development of the future? Indeed, some countries are considering their energetic and material strategies based only on economic aspects.

However, sustainable development moves a step further, thinks ahead, and deals wisely with the availability of bioresources beyond our children’s children. Circular economy is not a hype; it is an imperative necessity.

Society needs to deal urgently with pollution, global warming, overpopulation, urban sprawl, natural resource depletion, waste disposal, climate change, loss of biodiversity, deforestation, ocean acidification, ozone layer depletion, acid rain, water pollution, and public health issues.

Renewable Resources and Biorefineries is part of the solution.

This specialist book for renewable resources and biorefineries is intended to stimulate the transition from a fossil-based to the biobased economy.

Eduardo Jacob-Lopes and Leila Queiroz Zepka
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Introductory Chapter: Renewable Resources and Biorefineries

Mariana Manzoni Maroneze,
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Additional information is available at the end of the chapter

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1. Introduction

In the face of global challenges, strategies to reduce and replace fossil resources towards a sustainable bio-based economy have been developed in several countries across the globe [1]. These challenges include rapid depletion of fossil resources, growing global population, climate change, energy security, food and water security and soil destruction. In this sense, the long-term objectives to achieve the global bioeconomy will be to ensure food and health security, make energy provision more sustainable, explore renewable resources, make the more efficient use of resources and produce new bio-based materials [2].

Although there are many viewpoints about bioeconomy, the notion itself is quite straightforward. Basically, the bioeconomy is the strategy that utilizes 'green' materials instead of fossil-based materials to generate bioenergy, chemicals, food, feed and other bio-based products, with a low or no generation of waste. Within such an economy, sustainability and the efficient use of resources are the key components of its implementation at the social and industrial level [3, 4]. Apart from its ecological impact, bioeconomy is also intended to have socioeconomic benefits such as fostering economic competitiveness, meeting rising demand and counteracting resource depletion [5]. The concept of bioeconomy is quite broad and can encompass a range of sustainability strategies, such as biorefineries, that were defined by the International Energy Agency [6] as a sustainable processing of biomass into a spectrum of marketable products.

All resources containing non-fossil organic carbon, recently (<100 years) derived from agriculture (dedicated crops and residues), forestry, industries (process residues and leftovers), households (municipal solid waste and wastewaters) and aquaculture (algae and seaweeds), are considered bio-based resources or also called biomass. Biomass can also be classified into

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nonedible and edible. The latter case, generally represented by the use of vegetable oils for biofuel production, has been criticized by competing with the food supply [7, 8]. The most relevant classification of biomass for its integration into specific bio-based product chains is according to its major component, such as lignocellulose (lignin + cellulose + hemicellulose), carbohydrates, proteins and triglycerides [8].

This biomass can be untreated or may have undergone biochemical (fermentation or enzymatic conversion), thermochemical (combustion, gasification or pyrolysis), chemical (acid hydrolysis, synthesis or esterification) and mechanical processes (fractionation, pressing or size reduction), with the aim of depolymerizing and deoxygenating the biomass components [3, 7].

The products of major commercial importance produced in biorefineries are biofuels (biogas, syngas, hydrogen, biomethane, bioethanol, biodiesel and bio-oil), chemicals (fine chemicals, building blocks, bulk chemicals and bioactive compounds), organic acids (succinic, lactic and itaconic), polymers and resins (starch-based plastics, phenol resins and furan resins), biomaterials (wood panels, pulp, paper and cellulose), food and animal feed and fertilizers [9].

Despite the many advantages of biorefinery systems, it is essential that they simultaneously combine the three pillars of sustainability and aim to balance the environmental, economic and social aspects. For this task, tools are required to provide quantitative information about the sustainability of the process. To this end, the life cycle assessment (LCA) assumes the character of quantifying the potential environmental impacts of products, processes or services. This valuable tool should be used to expand the knowledge base of productive systems and their relationship with the environment, once it can increase the efficiency of its processes, reduce costs and, additionally, promote marketing of their products due to its appeal for sustainability [10].

This all suggests that bioeconomy is a necessity in order to pave the way to a more innovative, resource-efficient and competitive society that reconciles food security with the responsible use of renewable resources. The chapters presented in this book are intended to provide a deeper insight into the use of renewable resources through biorefinery systems to move towards a sustainable bioeconomy.

Conflict of interest

The authors declare that they have no conflict of interest.

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From Forest Biomass to Carbon Trading

Gun Mardiatmoko

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Abstract

The role of forest biomass is now greater due to its ability to cope with global warming. Facts prove that forest cover decreases have caused climate change and various disasters such as flood, landslide, drought, extreme weather, and others. Efforts to address climate change have been made by the international community through greenhouse gas (GHG) emission reduction programs with avoided deforestation and forest degradation through the afforestation/reforestation clean development mechanism (A/R CDM), reducing emission from deforestation and degradation (REDD+), joint implementation (JI), and voluntary carbon market (VCM) schemes. These programs are closely related with carbon trading. Carbon markets need a unit of trade. For carbon, this is one ton of greenhouse gas emissions expressed as carbon dioxide equivalents (tCO_2e). That is why measurement of forest biomass is very important. Methods to estimate forest biomass from models, inventory, remote sensing data, and geographical information system are being developed, evaluated, and demonstrated at several pilot regions in the world. Carbon markets are believed to be effective and efficient mechanisms in providing these financing sources. In carbon markets, prices are decisive in generating carbon credits. Higher carbon prices will cause more carbon credits to be generated. Nevertheless, carbon trading from REDD+ is found to be a concern especially for developing countries that is the risk of leakage and non-permanence. This chapter aims to inform the importance of measuring forest biomass as it is used as the basis for carbon accounting on carbon trading.

Keywords: forest biomass, carbon trading, leakage, permanence, additionality

1. Introduction

The role of forest biomass is now greater due to its ability to cope with global warming. Facts prove that forest cover decreases have caused climate change and various disasters such as flood, landslide, drought, extreme weather, and others. Global climate change is widely seen as one of the greatest environmental problems facing the twenty-first century [1–3]. The impacts resulting from this period of great change begin to take place, are felt and will affect the whole world, every ecosystem, every nation, and every human endeavor [4]. Scientific consensus points to emissions of greenhouse gases, largely from the burning of fossil fuels, as the primary culprit behind this problem [5]. In this regard, one important effort to reduce greenhouse gases in the atmosphere is to immediately replace fossil fuels with renewable energy sources.

In general, biomass is the total weight or volume of organisms in a given area or volume. Biomass is defined as the total amount of living matter above the surface of a tree and is expressed by tons of dry weight per unit area [6]. For forest, biomass itself is defined as the overall volume of living things of all species at a given time and can be divided into three main groups, viz. trees, shrubs, and other vegetation [7]. Forest biomass is highly relevant to climate change issues. Forest biomass plays an important role in the biogeochemical cycle, especially in the carbon cycle. From the total forest carbon, about 50% is stored in forest vegetation. As a consequence, forest damage, fire, logging or illegal logging, and so on will increase the amount of carbon in the atmosphere. In general, the dynamics of carbon in nature can be explained simply by the carbon cycle. The carbon cycle is a biogeochemical cycle that includes the exchange/transfer of carbon between the biosphere, the pedosphere, the geosphere, the hydrosphere, and the earth's atmosphere. The carbon cycle is actually a complex process and every process interacts with other processes. Plants will reduce the carbon in the atmosphere (CO_2) through the process of photosynthesis and store it in plant tissue. Until the time carbon is refluxed into the atmosphere, the carbon will occupy one of a number of carbon pools. All the components of the vegetation of trees, shrubs, lianas, and epiphytes are part of above biomass. Below the soil surface, plant roots are also carbon stores other than the soil itself. For example, in peat soils, the amount of carbon stores may be greater than the carbon deposits on the surface. Carbon is also stored in dead organic materials and biomass-based products such as wood products both when used or already in the landfill. Carbon can be stored in carbon pools for long periods or only briefly. Increasing the amount of carbon stored in this carbon pool represents the amount of carbon absorbed from the atmosphere [8]. The role of forest biomass is greater after having financial value in mechanism of carbon trading. Carbon markets need a unit of trade. For carbon, this is one ton of greenhouse gas emissions expressed as carbon dioxide equivalents (tCO_2e). Besides that, each greenhouse gas can be converted to a ton of CO_2e through multiplication by the global warming potential of the gas. This is the physics of the gas in the atmosphere that results in energy being absorbed rather than radiated out to space.

That is why there is much research on the measurement of forest biomass from all forest components. In its development, forest biomass measurements include all living biomass above- and below ground, such as trees, shrubs, palms, saplings, and other undersea plants, creeping plants, lianas, epiphytes, etc., and, in addition, biomass from dead plants such as dead wood and litter. Since carbon in the forest can be traded in the carbon market, an accurate mechanism for measuring forest biomass is required. Therefore, the purpose of this chapter is to inform the importance of measuring forest biomass as it forms the basis for carbon accounting on carbon trading.

2. Forest biomass

In general, forest biomass is the mass of the above-ground portion of live trees per unit area. It is a basic forest property linked to the productivity and processes of the forest ecosystem, and is an important indicator of the carbon stock that will help determine the contribution of forests to the global carbon cycle. Methods for estimating forest biomass have been largely undertaken from models or using allometric methods, forest inventory, applications of remote sensing data and geographical information system (GIS). The method has been widely practiced in various pilot areas in almost all countries in the world.

The allometric method for biomass assessment was first discovered by Kittredge [9] in the form of a logarithmic formulation as follows:

$$Y = aX^b \tag{1}$$

where Y = dependent variable (in this case, biomass content); X = independent variable (in this case, may be the trunk diameter or height of tree, root, wide tree canopy, etc.); and a, b = constants. Allometric method is a method of measuring plant growth expressed in terms of exponential relationships or logarithms between plant organs that occur harmoniously and changes proportionally [10]. The methods used to measure carbon content in forest biomass can be done in three ways as follows:

1. Total harvesting method: This method is commonly done to measure the content of biomass or carbon in vegetation of relatively small size, that is, for the level of shrubs and herbs, for example, the types of agricultural crops as a mixture of agroforestry, such as peanuts, corn, rice, soybeans, under plants, shrubs, grasses, and others.
2. Stratified clip method/allometric method: This method is usually done to measure the content of biomass or carbon in vegetation of relatively large size, such as poles and trees. Implementation of this method in the field is usually done by destruction of sample trees, then separating each section of plant organs that generally include roots, stems, branches, and leaves. Parts of the plant organs are weighed for wet weight (if possible) and sampled for drying (oven) to get biomass value. The biomass content or carbon content of each tree is associated with easily measurable growth variables, such as tree diameter and/or tree height. With the number of samples of varying sizes, the allometric equations can be obtained.
3. Estimation method: This method is done using commonly used assumptions to estimate the carbon content of forest vegetation. Some commonly used assumptions for estimating carbon content are as follows:

    a. carbon content of vegetation trees = 0.5 × biomass weight [11]

    b. forest carbon content = 80% × charcoal weight [12]

    c. stem biomass = stem volume × wood density

    d. total above-ground biomass (tree biomass above ground) = biomass stem × BEF (Biomass Expansion Factor).

4. The types of allometric equations formulated include allometric equations based on types of forest, types of tree, and the parts of trees. For example: *Swietenia mahogany*, $Y = 0.9029 (D^2.H)^{0.6840}$; *Dalbergia latifolia*, $Y = 0.7458 (D^2.H)^{0.6394}$; and Tectona grandis, $Y = 0.0149 (D^2.H)^{1.0835}$ where Y is the total biomass of trunk, branch, and leaf; D is the diameter at breast height; and H the total height. The total biomass of five combined tree species (*Swietenia mahogany, Dalbergia latifolia, Tectona grandis, Paraserianthes falcataria, and Acacia auriculiformis*) $Y = 0.0219(D^2.H)^{1.0102}$ [13]; $Y = 0.262 + 1.934 D$ where Y is the total liana biomass in tropical primary and secondary forests and D is the liana diameter; $Y = 2.55 + 0.416 L$, where Y is the stem biomass and L is the liana length [14]; for young rain tree or *Albizia saman*, $Y = -10{,}310.50 + 1820.89X_1 + 10.89X_2$ where X_1 = Diameter and X_2 = Height [15]. Besides that, there are also the relationships between above-ground dry plant biomass and stem diameter of liana [16] and bamboo [17–19]. Generally, several generalized allometric equations for tropical forests have been established and also widely used. Unfortunately, application of such generalized equations to individual sites may lead to large errors in biomass estimates especially when the species concerned is poorly represented by the generalized models. In this case, local allometric models are needed to give an accurate estimation [20].

In a forest carbon inventory, a calculated carbon pool contains at least four pools of carbon. The pools of carbon are above- and below-ground biomass, dead organic matter, and soil organic carbon.

1. The above-ground biomass is all living material above the ground, including stems, stumps, branches, bark, seeds, and leaves from the vegetation either from the strata of the tree or from the strata of the lower plants on the forest floor.
2. The below-ground biomass is all biomass of plant roots that is alive. This root meaning is valid up to a certain diameter set. This is done because plant roots with diameters smaller than the provisions tend to be difficult to distinguish from soil organic matter and also litter.
3. Dead organic materials include dead wood and litter. Litter declared as all organic materials die with a diameter smaller than the diameter that has been established with various levels of decomposition located at the ground surface. Dead wood is all dead organic matter that is not covered in litter either standing or falling on the ground, dead roots, and stumps with a diameter greater than the specified diameter.
4. Soil organic carbon contains carbon in mineral soil and soils organic including peat.

Remote sensing satellites have been used in many studies on forest biomass successfully. The use of remote sensing is increasingly widespread after supported by the use of spatial analysis in the geographical information system (GIS). That is why the making of forest biomass maps and other thematic maps has been done for many purposes. Remote sensing applications have been able to estimate forest structure and biophysical parameters such as land cover, crown closure, stand height, leaf area index, biomass, volume, etc. The advantages of remote sensing applications include systematic repetition scope with spectral and spatial consistency, the ability to monitor areas of interest over time, suitability for large area coverage, and a digital representation conducive to image processing. This is supported by satellite sensors capable of recording the reflectance spectra of the stands which is a combination of soil reflection spectrum, trees and ground vegetation. Stand reflectance depends on the relative amounts of these components within a ground resolution cell.

In relation to the search for renewable energy sources for the future, actual forest biomass such as felled and low-value trees can be an alternative in determining renewable energy sources or bioenergy. Thriving markets for these materials will add value to the working forests and provide an important tool for addressing a number of natural conservation goals, including hazardous fuel reduction, degraded forest restoration, habitat management, etc.

Available forest areas are limited by a number of non-market factors, such as environmental regulations, conservation efforts, the value of non-timber forest, and the behavior of landowners. In addition, economic factors will determine where biomass is available and its quantities. National policies of developed countries and global market mechanisms can improve the demand for woody biomass; then, the prices for these materials will tend to increase as well. The given high biomass prices will certainly benefit forest landowners and increase the bottom line for sustainable forest management. In terms of biomass, buyers will increase the cost for existing biomass users. In terms of the pricing process through supply and demand mechanisms in the market, increasing demand will lead energy producers into competition with forest products for timber and residues, or encourage timber harvesting to unsustainable levels. On the other hand, the forest products industry can afford higher prices for wood fibers than most energy producers can meet, due to the high value of wood, pulp/paper, and other wood products relative to energy values. Thus, the availability of biomass at low costs will limit where and to what extent bioenergy is seen as cost-effective. This is especially true as other renewable energy costs (such as wind, geothermal, solar, and water technology) continue to decline.Actually, the economic feasibility of bioenergy will depend on the supply of reliable and affordable raw materials. In this case, bioenergy has more in common with oil, natural gas, or coal than any other form of renewable energy, such as wind, geothermal, and solar. However, unlike fossil fuels, forest biomass is a living resource, subject to biological forces, climates, and natural disasters. Also, unlike fossil fuels, forests are much appreciated, more than just their energy content. People depend on forests for clean water, biodiversity, timber products, recreational opportunities, essential ecosystem services, and for their esthetic and spiritual appeal. The challenge is to build an infrastructure for cost-effective harvesting of reliable biomass supplies without negatively impacting these other values. The following recommendations address the need to develop infrastructure and an atmospheric biomass market that prioritizes conservation goals, ecosystem restoration, and other forest stewardship objectives.

3. Handling climate change

Efforts to address climate change have been made by the international community through greenhouse gas (GHG) emission reduction programs with avoided deforestation and forest degradation through the afforestation/reforestation clean development mechanism (A/R CDM), reducing emission from deforestation and degradation (REDD+), Joint Implementation (JI), and voluntary carbon market (VCM) schemes.

3.1. Afforestation/reforestation clean development mechanism (A/R CDM) scheme

The forestry CDM is a partnership between the developed and developing countries to reduce greenhouse gas (GHG) emission through the forestry activity: afforestation and reforestation. Principally, carbon trading will assist in reconstruction of forest ecology and forest protection in Indonesia. The actor of the forestry CDM is called the developer of the afforestation and reforestation project under the CDM. This developer is a union of two institutions between investor from developed country (Annex I of the United Nations Framework Convention on Climate Change/UNFCCC) and business sector by state or private company, cooperation, or personnel from the developing country. The Kyoto Protocol is a 1997 international treaty that came into force in 2005; it binds most developed nations to a cap-and-trade system for the six major green house gases. Emission quotas were agreed by each participating country, with the intention of reducing their overall emissions by 5.2% of their 1990 levels by the end of 2012. Under the treaty, for the five-year compliance period from 2008 until 2012, nations that emit less than their quota will be able to sell emissions credits to nations that exceed their quota. It is also possible for developed countries within the trading scheme to sponsor carbon projects that provide a reduction in green house gas emissions in other countries, as a way of generating trade-able carbon credits. The protocol allows this through CDM, in order to provide flexible mechanisms to aid regulated entities in meeting their compliance with their caps. The UNFCCC validates all CDM projects to ensure they create genuine additional savings and that there is no carbon leakage. The developer of the afforestation and reforestation project under the CDM can obtain Certificate of Emission Reductions (CERs) if they make: (1) project proposal of the afforestation and reforestation project under the CDM and (2) project design document for project activities under the CDM.

CDM projects labeled by the Gold Standard (GS CDM Project) must be verified by an independent auditor authorized by the United Nations and must meet more stringent requirements than regular CDM projects. This unique quality standard is chosen to demonstrate a broader CSR commitment and it is likely that the credits from the Gold Standard project will remain eligible in the future compliance regime. These high-quality carbon credits are often used by international banks, insurance companies, public authorities, or individuals [21].

In our opinion, the afforestation and reforestation project under the CDM is very flexible because it can be done at forest area, forest community area, state forest area, and private land. Land use change that can be done in the afforestation and reforestation project under the CDM is conversion from agriculture, wetland, settlement area, ranch area, or prairie to forest. The types of forestry activity for implementation of the afforestation and reforestation project under the CDM include agroforestry, silvofishery, rubber estate, monoculture and mixed species plantation, multipurpose species plantation, etc.

3.2. Reducing emission from deforestation and degradation (REDD+)

The Parties to the United Nations Framework Convention on Climate Change created an ambitious plan—the Paris Agreement—for global action on climate change mitigation and adaptation at the 21 Conference of the Parties in Paris in 2015. As part of the plan, the Paris Agreement promotes the adoption of policy approaches and positive incentives to reduce emissions from deforestation and forest degradation, the role of nature conservation, enhancement of forest carbon stocks, and sustainable forest management known as REDD+. The aim is to enable stakeholders to contribute to climate change mitigation. Countries in Africa, Latin America, and the Asia-Pacific region are working on their REDD+ strategy and developing an architecture to monitor, report, and verify emissions reductions [22].

REDD+ in international climate change policies is often championed as an important mechanism in response to the accepted fact that deforestation and forest degradation account for about 20% of global greenhouse emissions. Deforestation and forest degradation are the main causes of climate change. In this regard, REDD+ is understood as a multifaceted response mechanism, with targets including the protection and conservation of forest areas, reforestation, forest restoration, and sustainable forest management. Ultimately, REDD+ seeks to increase or conserve carbon stocks contained in forests, but the associated benefits of better forest conditions also provide lower ecosystem services. In addition, it also seeks to improve soil stability, provide livelihoods, maintain biodiversity, supply raw materials, and reduce flood risk [23].

Through this REDD+ program, carbon trading is possible in many countries. In the development of REDD+, implementation is still facing many obstacles, especially in developing countries such as in some countries of Asia and Africa. One of the obstacles to REDD+ implementation is the adoption of Forest Reference Emissions Level (FREL) used as a benchmark/country/territory reference to measure GHG emission reduction performance. This FREL needs to be prepared by meeting the requirements of the COP, in accordance with the technical assessment guidance, the application of the principles of transparency, accuracy, completeness, and consistency of data, as well as practicality and cost-effectiveness of its measurable, reportable, and variable (MRV) aspects. Through this national FREL, it is expected that the status and level of future GHG emission reduction will be measurable and monitored, and can be reported periodically. In the implementation of MRV aspects on REDD+, it is necessary to carefully measure forest biomass among others by the use of local allometric equations. Therefore, for a country with high biodiversity, it will certainly require many local allometric equations, and developing countries will have their own constraints in implementing it. Implementation of REDD+ requires long-term financial certainty and this will be realized if there is certainty in the carbon market.

3.3. Joint implementation

The definition of a joint implementation of Article 6 of the Kyoto Protocol provides the possibility for a country to reduce GHG emissions or a limiting commitment under the Kyoto Protocol (Annex B Party) to obtain emission reduction units (ERUs) from emission reductions or other Annex B party emission removal projects, with each unit equivalent to one ton of CO_2, which can be calculated to meet its Kyoto targets. JI provides the parties with a flexible and cost-effective way of fulfilling some of their Kyoto commitments, while the host party benefits from foreign investment and technology transfer. This project should provide for emission reductions by sources, or increased absorption by sinks, which is additional to what should have happened. The project shall have the consent of the host party and the participant shall be authorized to participate by the party involved in the project [24].

3.4. Voluntary carbon market (VCM) scheme

The voluntary carbon market (VCM) scheme is slightly different from CDM, REDD+, and JI. As part of the global carbon market, the voluntary CO_2 market differs from the compliance schemes under the Kyoto Protocol and the EU-ETS. Rather than undergoing the national approval of project participants and the registration and verification process of the United Nations Framework Convention on Climate Change (UNFCCC), the calculation and certification of emissions reductions are carried out in accordance with a number of industry-made standards. The advantage of lower development or transaction costs makes the voluntary market particularly attractive to small and sustainable projects where the UN certification process is too expensive.

Compared with compliance markets such as EU-ETS, the total size of the voluntary CO_2 market is much smaller. The credits coming from the voluntary CO_2 market are called voluntary emission reductions (VERs). Currently, VER is mostly used by companies that want to voluntarily offset the emissions generated during their business activities to demonstrate social responsibility and build a healthy and green corporate image. More companies are investing in VER projects to reduce their carbon footprint and to achieve "zero emission" status.

4. Carbon trading

Carbon trading is a market-based mechanism for helping mitigate the increase of CO_2 in the atmosphere. Carbon trading markets are developed to bring buyers and sellers of carbon credits together with standardized rules of trade. Any entity, typically a business, that emits CO_2 to the atmosphere may have an interest or may be required by law to balance their emissions through the mechanism of carbon sequestration. These businesses may include power-generating facilities or many kinds of manufacturers. Entities that manage forest or agricultural land might sell carbon credits based on the accumulation of carbon in their forest trees or agricultural soils. Similarly, business entities that reduce their carbon emission may be able to sell their reductions to other emitters. The legal aspect of carbon trading is CERs. In other words, carbon trading is a market mechanism for reducing GHG emissions. The idea is to price the carbon so that the activities that emit GHG become expensive. The carbon trading section allows companies to buy and sell carbon credits on the carbon market. Therefore, companies can continue to produce GHG as long as they can buy enough credit to cover their emissions. In addition, the credit market also allows the government to ramp prices by controlling credit supply, thus accelerating the transition away from activities that release GHG [25].

Like other goods or services, the price of carbon credits in carbon trading is established by the intersection of supply and demand. Contrary to regulated markets where supply and demand for carbon credits are regulated through complex regulation, supply and demand for carbon credits respond to free market transactions.

One of the factors that support the determination of carbon trading is the rise in energy prices in the world. This encourages people to reduce their consumption and lower their personal share of global emissions. But beyond that, there is actually a growing framework of economic solutions to this problem. Two major market-based options exist, and politicians around the world have largely settled on carbon trading over their rivals, the carbon tax, as the method chosen to regulate GHG emissions. In carbon trading is not separated by the carbon tax. The alternative to markets for carbon prices is to impose a carbon tax. It has never been a popular choice with voters and is government-dependent to act reasonably both in how they impose the tax and what they do with revenues. Therefore, for taxes to have a mitigating effect on global warming, governments need to spend on revenues for schemes that reduce emissions or buy carbon credits so that net emissions are reduced. Carbon trading takes pressure from governments to source and fund emissions reductions because price pressures make activity change. Emitter must buy permission or credit in the market to balance (offset) the equivalent carbon dioxide that they directly or indirectly release into the atmosphere.

Once a carbon market is formed, buyers and sellers can bargain prices and volumes. In fact, carbon trading becomes complicated because buyers, who recall being forced to buy credits to offset the reported emissions, look for the best prices. Soon, all sorts of financial mechanisms emerge to protect themselves from risks, minimize costs, and make deals. Secondary markets in on-selling, bundling, and derivative credits will emerge that outstrip the volume and market value for primary credits. Sellers are those who have generated carbon credits from emission reduction projects, reductions or sequestration that generate carbon offsets, or have allocated credit.

In the free market, supply and demand will determine the price. However, the carbon market is not a free market because the reason for carbon trading is to reduce GHG emissions. One of the problems in carbon trading is the declining carbon price. To ensure the increase in the carbon price, the number of permits and credits allowed in the limited system is the cap. Supply cannot meet demand and the price goes up. This is what is known as the cap-and-trade system. Initially, demand will continue to increase along with rising emissions. This emission will occur only as a result of economic growth which is the foundation of the capitalist economic system and a necessity when the human population grows at 8,000 per hour. Limits on credit supply can be achieved by limiting the issuance of faux credits (emissions allowances or permits) and real credits resulting from mitigation, reduction, and reimbursement projects. Thus, there will be a balance. In this case, there should be enough credit to meet the demand because the issuer is forced to pay. In addition, carbon markets should also create opportunities for cost savings, but the price per credit also needs to rise [25].

Sometimes, carbon trading is called emissions trading, as it is a market-based tool for limiting GHG. The carbon market trades emissions under a cap-and-trade scheme or with credits that pay or offset the reduction of GHG [26]. The cap-and-trade scheme is the most popular way to regulate carbon dioxide (CO_2) and other emissions. The scheme's governing body begins by setting a cap on allowable emissions. It then distributes or auctions off emissions allowances that total the cap. Member companies or firms that do not have enough allowances to cover their emissions must either deduct or purchase another company's reserve credit. Members with extra allowances may sell it or give it to the bank for future use. In practice, the cap-and-trade scheme can be either mandatory or voluntary.

Success of the cap-and-trade scheme relies heavily on strict but feasible constraints that reduce emissions over time. If the cap is too high, excess emissions will enter the atmosphere and the scheme will not affect the environment. A high cap can also decrease the value of benefits, causing losses to firms that have reduced their emissions and banked credit. If the cap is too low, its allowances are scarce and too expensive. Some cap-and-trade schemes have a safety valve to keep the value of allowance within a certain range. If the allowance price is too high, the scheme's governing body will release additional credits to stabilize the price. The price of allowances is usually a supply-and-demand function. Credits are similar to carbon offsets except that they are often used in conjunction with a cap-and-trade scheme. Firms wishing to reduce the targets can fund pre-approved emission reduction projects on other sites or even in other countries.

From the above description, carbon trading is actually a clever set of ideas that utilize market mechanisms that have been sharpened from generation to generation in capitalist economy. Of course, this will allow some investors to make serious money, and it fits with the adverse risks in the midst of current politics. Furthermore, these ideas will change our greenhouse gas emissions because, in time, it will be too expensive to release greenhouse gases. Unfortunately, no one is really sure if carbon trading will be able to change it fast enough [25].

5. Implementation of REDD+ in relation to risk, financing, and implementation strategies

The occurrence of deforestation and forest degradation, especially in developing countries, has accounted for nearly 20% of global GHG emissions. From various literatures, it can be used to limit the impacts of climate change in which the global community is able to cope with stabilizing the average of 20°C. REDD is an attempt to evaluate the value of carbon stored in forests and offer incentives for developing countries that have managed to reduce emissions from forest land and invest in low-carbon paths for sustainable development. The scope of REDD is then expanded by incorporating conservation roles, and increasing forest carbon stocks (REDD+). Implementation of REDD+ related to the Principles of National Approach and Sub-national implementation can be effectively applied to reduce the emissions if each stakeholder can make efforts to reduction of carbon emissions.

For the development of REDD+ activities, the commitment itself is highly dependent on the management of applied management in order to overcome the uncertainties in the field leading to the termination of commitment or non-permanence. This is due to the high competitiveness of land-based commodities around REDD+ sites. Competitiveness itself is influenced by the cost borne by the developer. Of course for developers to keep that commitment very closely related to how to get certainty to get REDD+ financing. As to the certainty of financing, the strategies that can be applied to maintain the commitment can be divided into two, viz. the institutional and distribution funding aspects. Institutional aspects include the strategy of enacting REDD+ sites as protected areas, implementing adaptive payment schemes that are a combination of input and performance-based mechanisms and buffer provision as a guarantee, and optimization of co-benefits. The funding distribution aspect includes the use of an existing funding channel, through government channels or fiscal transfers, the establishment of a new and verifiable government funding agency REDD+ and verification by a third party. With regard to transaction costs, the first and second strategies are believed to be lower than the third strategy.

Actually, REDD+ can be an effective incentive mechanism and efficient in reducing emissions. The incentives in question are benefits derived from REDD activities in the form of financial support and/or technology transfer and/or enforcement. Thus, the incentive scope may be in the form of monetary or non-monetary incentives. The success of running REDD+ is very much in line with the policy used for the expenses incurred. In other words, the scope of activities in REDD+ implementation for the purpose of reducing carbon emissions will definitely bring other benefits such as co-benefits, environmental services, forest sustainability, biodiversity, etc. However, the performance of REDD+ implementation is measured by looking at the ability of developers in reducing carbon emissions. This problem is related to the amount of carbon emission reductions generated through the measurable, reportable, and variable (MRV) system.

In addition, REDD+ also has negative impacts such as reduced public access to forest resources, reduced forest industry investment, and reduced forest sector economic contribution. The pressure on the existence of forests takes place in various forms of activities such as encroachment, illegal logging that occurs as a result of low socioeconomic conditions of people or below the poverty line. Pressure on REDD+ sustainability will certainly increase as commodity prices increase and as lands are used for agriculture, plantation, mining, etc. These pressures need to be considered as they relate to lower REDD+ competitiveness compared to other land-based commodities such as palm oil, coconut, and mining. This is indicated by the price per ton of carbon that must be applied to compensate the costs of other businesses such as oil palm and rubber plantations. The competitiveness of REDD+ can also be low again due to the high transaction costs that must be incurred. The high cost of such transactions is usually due to the lengthy process of issuing and trading certificates of reducing forest carbon emissions. Transaction costs in the production process are undesirable costs because the existence of these transaction costs makes commodity prices inefficient as prices become more expensive and tradable goods become less.

It should be emphasized, however, that transaction costs in REDD+ implementation are costs that must be taken into account. This is related to institutional costs inherent in REDD+ implementation, at least cost for contracting, searching and disseminating information, handling conflicts of interest that occur between stakeholders, validation and verification activities, and certification of emission reduction and credit buffer in case of leakage and non-permanence. The transaction costs will also increase in line with the intensive coordination between stakeholders involved as an effort to avoid conflict between stakeholders [27]. The effect of transaction costs on the price and quantity of carbon is presented in **Figure 1.**

5.1. Types of risks facing REDD+ and project financing

The key to successful implementation of REDD+ is the implementation of carbon conservation activities properly and correctly. Carbon conservation activities will have a major impact on the economy and the environment. The carbon conservation effort will have an

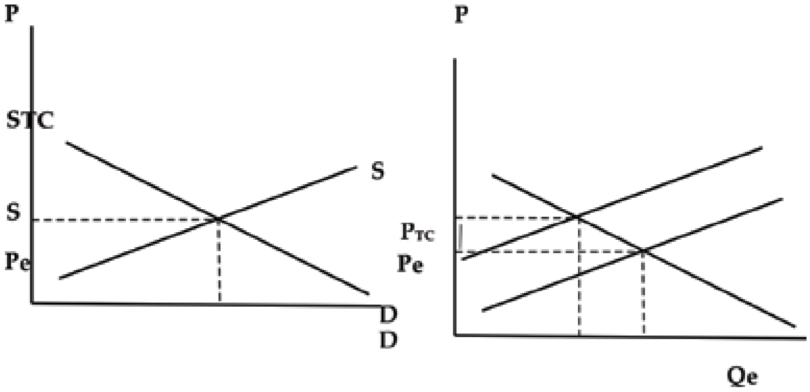

Figure 1. The effect of transaction costs on the price and quantity of carbon.

impact on the presence of carbon co-benefits such as biodiversity, community empowerment, employment creation, and other livelihood creation. However, there are also negative impacts such as "reducing access" of the community or the private sector in the management of forest resources. In general, the risks faced in implementing REDD+ are leakage and non-permanence. Leakage illustrates the occurrence of emissions that occur outside the project site. Leakage that occurs will reduce the amount of carbon credits generated. The opposite of leakage is additionality, which means increasing the amount of carbon produced. To facilitate the understanding of leakage and additionality, illustrations are presented in **Figure 2.**

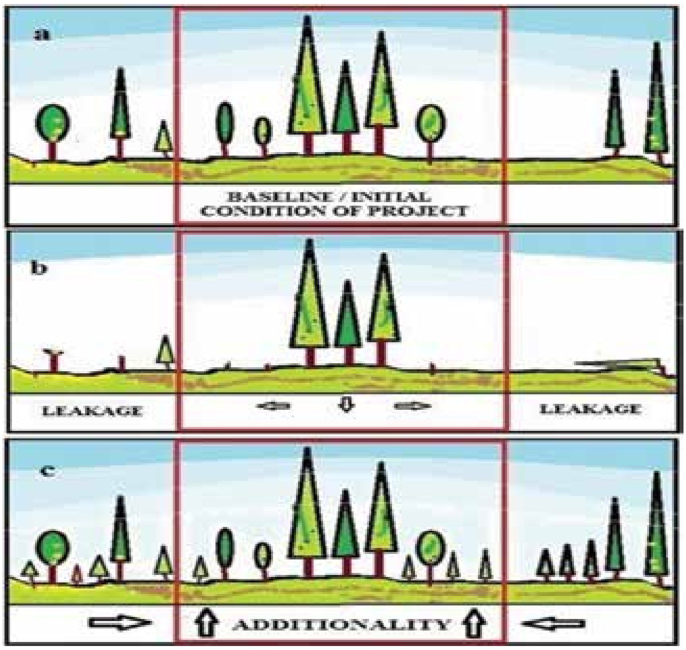

Figure 2. (a) Baseline, (b) Leakage, and (c) Additionality.

Sufficient knowledge of the source of leakage is important to develop a clear strategy for dealing with leakage issues. The risk of this leak may increase in line with: (1) opening of new business land for agricultural purposes and offsite plantations. Such encroachment activities may occur in other locations, and (2) the occurrence of encroachment or illegal logging activities tend to occur outside of the locations devoted to REDD+. The risk of non-permanence is associated with increased carbon emissions resulting from reduced management commitments to maintain REDD+ activities during the project or post-project completion. This can happen as a result of the project manager's ability to reduce carbon emissions. One of the factors driving irresponsibility is the absence of long-term financing planning. This leads to uncertainty in financing activities. This inadequacy increases in line with the increased cost of logging or the value of land for agriculture or plantation or other higher land use. In addition, this lack of permanence is also driven by the lack of clarity on incentive mechanisms and the benefits of REDD+ activities. This condition is usually exacerbated by the weakness of law enforcement. Increased dependence on increased forest resources is a result of declining public purchasing power due to the absence of alternative livelihoods among the project-related communities. Successful implementation of REDD+ is highly dependent on developer access to capital or financing sources. In addition, the seriousness of the developers also depends on how the implementation of REDD+ is able to compete with other uses, especially plantations and agriculture. This problem is related to the risk of failure of REDD+ implementation by leakage of non-permanence.

As with other land-based carbon business activities such as the forestry CDM, REDD+ implementation faces long-term financing issues. Given that REDD+ is a long-term program and requires huge financing. The availability of long-term financing is an indicator of developer commitment in REDD+ implementation. This is related to the risks faced by the developer of leakage and non-permanence. With regard to financial flow, there are currently two alternative incentive mechanisms, namely input-based mechanism (IBM) and result-based mechanism. Both are donors funding flows to REDD+ implementers or developers. IBM is a stream of funds tailored to the needs of REDD+ implementation. The amount of funds is not related to the emission reduction performance achieved. While RBM is a stream of funds whose amount depends on the amount of emission reductions achieved. The amount of carbon credits generated in this RBM is highly dependent on the additionality obtained. If project financing occurs through RBM, then the receipt of the developer will depend on the applicable price or the deal price of the buyer. In this situation, the developer must be a company that has strong capital and has a strong commitment to conservation activities so that the company is able to generate verified carbon credits [27].

5.2. Strategy to overcome leakage and non-permanent risk

The REDD+ and socioeconomic conditions around the project site define the developer strategy in addressing the risks in order to ensure that it. Increasing public demand on land due to decreasing public purchasing power as a result of rising food prices. In addition, higher competitiveness of other land-based enterprises such as plantations, mining, and agriculture is the driving force behind non-permanence. Considering that REDD+ is an activity with national and subnational approach and is related to national commitment to reduce GHG emission, financing certainty is required. Based on stakeholder perception, the first strategy applied is through the implementation of disincentives for developers who cannot guarantee permanence of activities. This is related to the commitment of REDD+ developers. Efforts are needed to facilitate the implementation of the strategy, then the government can issue a policy that regulates the status of REDD+ project location as a protected area. Implementation of this strategy encourages developers to ensure certainty of performance reduction of carbon emissions achieved. The next strategy is to implement an adaptive payment scheme, in which payments received by the developer are in line with the dynamics that occur. This strategy is linked to REDD+ financing mechanisms. This adaptive payment is a combination between IBM and RBM. Developers are eligible to receive early or periodic or annual payments as per performance results for REDD+ activities. Other strategies that can be pursued are to optimize the management and utilization of existing co-benefits within the site and set up the reserve area to cover potential losses [27]. The commitment of developers of REDD+ activities will be maintained if REDD+ funding distribution is acceptable to developers effectively and efficiently. Funding certainty for REDD+ activities will work effectively if it has a clear institutional funding distribution. The effectiveness of the channeling can be achieved if using existing government channels in the form of fiscal transfers. Donors can channel their funds through government agencies (national and subnational), then the government agencies channel them to developers. The second strategy is the transfer of funding through a REDD+ agency verified by the national government. The involvement of government agencies is believed to minimize transaction costs faced by developers. This transfer mechanism requires the establishment of a REDD+ financial institution first. The third strategy is the same as the second strategy, but incoming and transferred funds must be verified first by an independent third party. Nevertheless, this strategy will have the opportunity to bring in high transaction costs.

Carbon markets are believed to be effective and efficient mechanisms in providing these financing sources. In carbon markets, prices are decisive in generating carbon credits. Higher carbon prices will cause more carbon credits to be generated. Nevertheless, carbon trading from REDD+ is found to be a concern especially for developing countries that is the risk of leakage and non-permanence. Transactions that occur in the carbon market are based on the amount of carbon credits traded. In fact, the resulting forest carbon credits are difficult to verify because a strong measurement methodology is required. Thus, the amount of carbon credits generated depends largely on: baseline and measurement methodology, additionality, sustainability or permanence, and leakage rates.

This condition is particularly difficult for developing countries because there is still a need for development in the country that still requires forest conversion for other uses, for example, urban development, expansion of infrastructure, transportation, expansion of agricultural land and plantations, settlements, and others. Seen from the demand side of the carbon market, the success of REDD+ implementation is also highly dependent on the commitment of developed countries that are obliged to reduce greenhouse gases. In its development, demand for carbon credits is dominated by carbon credits from non-land-based sectors. It turns out that carbon credits in the market globally are dominated by the energy sector. This will lead to an oversupply of carbon credits in the European carbon market. As a result, there is a tendency to decrease the value of carbon credit transactions not only in the European carbon market but in all carbon markets. It is feared that increasing carbon credits from REDD+ to existing carbon markets will lead to over carbon credits in the carbon market, resulting in lower carbon prices. The amount of carbon credits from REDD+ is equivalent to a decrease in deforestation and forest degradation rates. Of course, it will be burdensome for developing countries. It is not worth the sacrifice of a developing country if the carbon credits generated by nobody pay primarily from developed countries. In our opinion, the implementation of REDD+ still involves a lot of harm, especially for developing countries associated with leakage, permanence, and additionality. Even Conservation bytes [28] calls these three things "Unholy trinity of leakage, permanence and additionality."

5.3. Unholy trinity of leakage, permanence, and additionality

The problem with REDD is that it is a wonderful thing to be given on some niggly issues that basically revolve around trust. Ah yes, bugbear from every business transaction. As “buyers” of carbon credits (companies or nations or individuals who want to offset their carbon output by “buying” carbon uptake provided by intact forests), we definitely want to make sure that all the money we spend to offset our carbon is actually just that, not just ending up in the hands of some corrupt officials, or even worse, are used to produce an industry that produces higher emissions! Of course, as a buyer we want to attract investors to give us a lot of money. If we interrupt the transaction, we will not have any more investors who come knocking on our door. Enter an unholy trinity of leaks, permanence, and additions. Imagine we are legislators and must make sure that buyers and sellers do not do anything clever and fall into one or all of the leak, eternal, or additional traps. Sounds like a terrible job, and probably not possible. How do we manage it and how long is "permanent"? How do we prove “what will happen”? So, basically we can imagine this unholy trinity has dropped many proposed REDD projects, and even kill that has been going on for some time. Like communism, that's a good idea, but REDD is almost impossible to make a job in the real world for many of the same reasons that communism fails—human greed and pettiness. Efforts to force such obstacles in the sky to avoid leaks and ensure timelessness and addition are actually more dangerous than good because so many programs fail even to get started. Further REDD+ implementation needs to be improved by including an insurance policy element called iREDD [28].

iREDD basically functions as follows: Before changing hands, the buyer and seller request an insurance brokerage service to assign premiums based on a priori assessment of any issues that may be related to leakage, immortality, and additions. Here, the Likert scale is used to rate proposals based on five criteria: (1) government structure—are the institutions reputable? Do they have a good business history?; (2) management plan—is the plan for managing REDD forests detailed enough to account for unforeseen events?; (3) project liquidity—do the institutions involved have sufficient cash flow to ensure they can meet the objectives of the management plan?; (4) acceptance—is the project acceptable to the community in the region? Do other groups support it?; and (5) purchase-politics—is the project included in the long-term plan of the relevant government agency? Is that against anything?

Once a rating is made, certain components of the money invested are used to purchase a scaled insurance policy against the identified (and approved) risks. If the seller (i.e., the recipient of funds and forest managers) fails to keep the forest intact, or it is subject to a destructive forest fire or political unrest, the buyer receives at least part of the premium as an out-of-pocket insurance payment. However, if the seller is true to their word (contractual obligations), the premiums and the interest are paid to them other than the money originally invested. In other words, everyone wins. If the seller fails, the buyer is compensated and can invest elsewhere. If the seller is good, they get more money. Most importantly, it increases the likelihood that atmospheric carbon will decrease and forest-related biodiversity will remain [29].

6. Conclusion

The role of forest biomass is now greater due to its ability to cope with global warming. The facts prove that forest cover decreases have caused climate change and various disasters such as flood, landslide, drought, extreme weather, and others. Efforts to address climate change have been made by the international community through GHG emission reduction programs with avoided deforestation and forest degradation through the forestry CDM, REDD+, Joint Implementation, and Voluntary Carbon Market schemes. This is closely related to carbon trading.

Since forest carbon has become a tradable commodity in the carbon market, forest biomass measurements are essential. Although there have been various programs to reduce GHG emission such as REDD+, there are still weaknesses such as the tendency of carbon prices to fall. This is certainly very detrimental, especially for developing countries that generally act as a seller of carbon. Therefore, much effort is needed to improve REDD+ so that the carbon trading mechanism can provide a satisfactory price for both sellers and buyers of carbon. One of the efforts undertaken, among others, is incorporating an element of insurance policy named after iREDD. With the insurance policy, concerns about the implementation of REDD+ related to leakage, permanence, and additionality can be reduced.

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Solid Biomass from Forest Trees to Energy: A Review

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Additional information is available at the end of the chapter

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Abstract

Among the different terrestrial ecosystems, forests are the most important biomass carbon producers and the ones that store the most standing biomass carbon. Consequently, they are also the major source of biomass for energy. Forest biomass has been used as a fuel from early times, and from the late twentieth century onward, there has been a renewed interest in its use to produce heat and electricity. The interest in forest biomass as an energy source relates to some of its features, such as relative abundance and uniformity worldwide and neutrality of CO_2 emissions. Nonetheless, its use is not free of risks, mostly related with the sustainability of the forest systems and their productions. This study reviews the state of the art of the forest sources of biomass for energy, their assessment, their properties as a fuel, as well as the conversion technologies used in the most common energy applications.

Keywords: silviculture, estimation, remote sensing, conversion technologies, heat, power

1. Introduction

Energy has been obtained from forests for thousands of years, forests being the largest contributor to the current global biomass supply [1]. Most of today's production of solid biomass for energy occurs in non-Organization for Economic Cooperation and Development (OECD) countries (in 2015, 83.7%) [2] and is widely used for traditional cooking and residential heating. The traditional use of biomass is inefficient and characterized by severe negative impacts on human health by the combustion smoke [3]. Also, it has been linked to local deforestation and consequent environmental degradation, but the association of the demand of traditional wood for cooking and heating to large-scale deforestation is controversial [4, 5]. The modern uses of woody biomass are characterized by more efficient and cleaner technologies. Its utilization, though, is also linked to controversies as far as sustainability issues are concerned. In developed countries, the interest in bioenergy has been increasing mostly due to greenhouse gas mitigation policies. Wood biomass is a renewable energy source and considered to contribute to a decrease in the anthropogenic CO_2 emissions. This chapter reviews the forest structure (Section 2), the existing methods and techniques to evaluate biomass (Section 3), the types of biomass and biomass residues (Section 4), and the common uses of biomass for energy (Section 5).

2. Forest structure and biomass

The role of forests in providing a large suite of products and services is well known [6–9]. Due to the reduction of the forest area and shortage of woody products, as well as to guarantee the sustainability of forests and ecosystems, the need to evaluate, monitor, and regulate the forest arose [10–12]. Initially, the emphasis of assessment was on the quantity per class of woody products (mainly large- and small-dimension timber), typically with the evaluation of volume [6, 13, 14]. This drove forest stands toward predominantly pure, even-aged stands, either in high forest or in coppice regime, frequently centered in one production, also due to the simpler management [6, 7, 10, 13, 14]. Later in the twentieth century, the stand and forest management were expected to include objectives other than woody products, such as services, sustainability, and conservation of the forests and ecosystems [10, 11]. This originated a shift in forest management to new approaches focused on systems of multiple productions, which have driven silviculture toward uneven-aged and mixed stands. These approaches are focused in the natural processes emulation, which originated a wide suite of methods and techniques to achieve it [10, 15–17]. The overall biomass production, as a result of the management approaches, tends to be periodical in even-aged stands with large time periods between two consecutive harvests, while multiaged stands harvest periodicity tends to be in shorter time periods and rather constant, with a quantity function of the growth, target equilibrium, and proportions of the age classes of the stand [6, 7, 10, 13, 14, 17, 18]. Stand composition, both on the quantity, variety, and quality of biomass, also derives from the management strategy. In the traditional approach, silviculture was oriented toward pure stands, while the new ones are focused on mixed stands. The latter are systems with wider complexity and consequently more difficult to manage but are considered more biodiverse and resilient, and enable risk dispersion due to their multiple productions [6, 7, 10, 14, 18–20]. The challenge is defining and separating pure and mixed stands [21].

3. Forest biomass evaluation

Forest evaluation started with forest inventories in the Middle Ages, during wood shortage, with the aim of estimating the forest areas, stand composition, and wood volume per dimension class. The expectations, apart from wood, of forests to provide services resulted in the inclusion of a wide set of variables in the inventories, among which is biomass [22–25]; this intensified labor and increased costs [22, 24]. Forest inventories are defined by sampling design, for an assumed threshold error, which is accomplished in two sequential steps: (1) evaluation of forest area and crown cover with remote sensing [24, 26, 27] and (2) survey of field plots to measure several dendrometric variables, being the most frequent diameter at breast height and total height [22, 24, 28–30]. The evaluation on an area basis is done with extrapolation methods [22, 24]. From the 1990s of the last century onward, the development of remote sensing deployed the derivation of a set of functions to estimate several stand absolute density measures such as the number of trees, the basal area, the volume, and the biomass (*e.g.*, [31–36]). These functions enable the rationalization of forest inventory field work, facilitating also the evaluation of forest stands where field work is hard to accomplish [22, 24].

3.1. Forest inventory

Biomass was not traditionally assessed in the forest inventories. It was only from the late twentieth century onward that it was included, compelled by the need to evaluate carbon stocks, sequestration and losses, and biomass for bioenergy. The methods to evaluate biomass can be grouped in two broad classes [22, 24]: the direct methods and the indirect methods. The former, though very accurate, are destructive and frequently used to derive data sets for modeling. The latter are mathematical functions that use as explanatory variables dendrometric variables, frequently diameter at breast height and/or total height. These functions are frequently developed for each biomass component (stem, bark, leaves, branches, and crown), and total tree biomass is obtained by summing all the components. Similarly, biomass per plot is the sum of the biomass of all the trees, and normally referred to a standard area unit, typically the hectare. The functions are species-specific, site-specific, and regime-specific, due to the tree species habit and growth pattern per site and regeneration method (seed for high forest and vegetative for coppice). As a result, a wide range of functions is found in literature [37–45]. The advantage of these functions is their accuracy [27]. The shortcomings are related to the selection of the best function for the stand location, species, and stand structure [46, 47]. The choice might encompass some difficulties when no functions exist or those that exist are not adequate, thus resulting in large estimation bias [48]; and with the extrapolation methods in the evaluation of the forest areas [24], decreasing the accuracy with the increase of the area evaluated due to the variation in stand structure, topography, soil, and climate [49]. The estimation errors with this method are assumed to be between 15 and 40%, with the standard threshold of 25% [50].

3.2. Remote sensing

The major advantage of remote sensing is related to the wide range of working scales, associated with the spectral, spatial, radioactive, and temporal resolutions, as well as to their technology [51, 52], which allow the evaluation of the distribution of the forest area, species, and their physical and biochemical properties [53]. The advantages of biomass estimation with remote sensing methods when compared with those using forest inventory are: (1) can be applied regardless of the area dimension [26, 27], (2) does not need field work, therefore being interesting in areas where it is difficult to implement it or where many field plots are needed to attain the threshold error [24, 27]; (3) short time cycles can be used for data collection, contrary to forest inventory, where cycles shorter than 5–10 years are unfeasible [24, 26]; (4) different scales can be used as function of imagery spatial resolution [26, 27]; and (5) it applies to all the area, thus extrapolation methods are not required [32, 34–36].

The biomass functions that use satellite image data are mathematical functions that use data derived from satellite optical sensors for the explanatory variable [33], such as spectral reflectance, crown diameter, crown horizontal projection, crown cover, original bands and/or vegetation indices [32, 34–36, 54–58]. The statistical methods and techniques used to fit the functions are varied. Examples are linear and nonlinear regression, regression k-nearest neighbor, neural networks, regression tree, random forest, and support vector machine [27, 52]. Remote sensing data is derived from passive or active sensors.

For an optical sensor (passive sensor), the spatial resolution is the main distinctive feature of the satellite images and can be grouped in three broad classes: coarse, medium, and high. The *coarse spatial resolution* satellite imagery (>100 m) comprises: National Oceanic and Atmosphere Administration (NOAA) with the Advanced Very High Resolution Radiometer (AVHRR) sensor, Moderate Resolution Imaging Spectroradiometer (MODIS), and Satellite *Pour l'Observation de la Terre* (SPOT) Vegetation [55, 59–62]. The *medium spatial resolution* satellite imagery (10 to 100 m) includes Landsat, Sentinel, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and Wide Field Sensors (WiFS) [55, 63–65], as well as recently Landsat 8 and Sentinel, free global-scale remote sensing data. The *high spatial resolution* satellite imagery consists of: IKONOS, QuickBird, WordView, and GeoEye satellites, with a pixel size smaller than 5 m [33–36, 66, 67].

The active sensors, Radio Detection and Ranging (RADAR) and Light Detection and Ranging (LiDAR), have gained relevance for biomass estimation in the last years [68–72]. The RADAR use microwaves to obtain information of surface target. It has the advantage of data acquisition being independent of the hour of the day and atmospheric conditions. More recently, the synthetic aperture radar (SAR) sensor, C-band RADARSAT-2, and X-band TerraSAR provide more accurate biomass estimation due to the spatial resolution variability, polarization, and incidence angles [73]. LiDAR systems allow to obtain detailed information about the structure of vegetation (horizontal and vertical tree dimension), considering the distances measured to the object surface [74, 75]. It can be supported by spaceborne, airborne, and terrestrial platforms that create a very precise 3D-point cloud data from vegetation [76] and are used to develop models for several vegetation biophysical parameters, such as tree height, crown dimensions, volume, and canopy density [52]. The statistical methods most frequently used to develop biomass functions are linear and multilinear regression [52] and machine learning algorithms [70, 71].

Some studies used a combination of LiDAR and multispectral or hyperspectral data to identify the different forest areas where the spectral response is similar, to improve the biomass estimation [77–81]. Related to the satellite spatial resolution is the target area of estimation, which can be at regional or local scales [32, 34–36, 82–86] or national scales [87–90]. However, some difficulties in the estimation of biomass with accuracy may arise due to the variability of the stands and forests, especially in the tropical forests [91, 92].

4. Forest biomass and forest residues

Forests are the terrestrial ecosystems that produce and store the most biomass, which explains why biomass for energy has been derived mainly from forests for a long time [8, 13, 14, 93, 94]. The forest biomass varies according to site, stand structure, topography, climate, management system, and disturbances [91, 95, 96]. The two features that make biomass a primordial source for energy are their availability and uniformity at a global level [8, 97, 98]; more recently, the neutrality in CO_2 emissions is also an important factor [97, 99].

In general, all forests produce biomass that is mainly removed in harvests, though in smaller quantities also in silvicultural operations (thinnings and prunings). Forests can be grouped in two broad types considering the biomass removal for energy purposes [95, 100]: energy plantations, where all biomass is harvested for energy and forest systems managed for timber and/or other products and services, where all or part of forest residues can be removed from the stands for energy purposes.

4.1. Energy plantations

Several terms have been used to describe the forest systems whose main, and frequently the only, production is biomass for energy [94, 101, 102] and that are characterized by specific spatial and temporal features [93, 99]. The most important features of these systems, when compared with agricultural crops or other forest systems, are their low risks, high economic viability, harvest flexibility, availability worldwide, biodiversity enhancement (especially if incorporated in agricultural crops portfolio), and the possibility of use for phytoremediation purposes [97, 100, 103–107]. The energy plantations are well represented in Europe, though to a lesser extent in the southern countries [103, 105], USA [108, 109], Canada [110], and China [111]. For the establishment of the energy plantations, the selection of species, density, rotation, harvest cycles, site, and management practices has to be considered.

The ***selection of species*** is of primordial importance. The species better suited for energy plantations are those that have high biomass production in dry weight, good sprouting ability, fast juvenile growth, narrow crowns or large-sized leaves in the upper crown, biomass with high specific energy and quality, adaptability to a wide range of sites, and resistance to biotic and abiotic agents [100, 112, 113]. Hybrids are frequently used to increase productivity, for their adaptation to the environmental conditions and resistance to pathogens [104, 114, 115]. From the many potential species suited for energy plantations, the three most referred in literature are: *Populus* spp. [101, 111, 112, 115–118], *Salix* spp. [101, 112, 114, 116, 118], and *Eucalyptus* spp. [97, 101, 112, 119, 120].

Density, rotation, and ***harvest cycles*** are strictly linked, since the main goal of energy plantations is to attain the highest production in the shortest time (*e.g.*, [104, 116, 117]). Thus, three principles regulate density and rotation; namely the law of final constant yield, the development of social classes in a stand, and self-thinning law [93]. However, there is a large variability of densities from 1000 stems ha^{-1} to 310,000 stems ha^{-1} [99, 108, 114, 116, 118, 121, 122] and rotation lengths between 1 and 20 years [99, 108, 114, 116, 118, 121, 122]. Also, a dichotomy seems to exist between density and rotation [101], frequently higher densities and shorter rotations [104, 114, 115, 121, 122], or lower densities and longer rotations [97, 118–120]. Harvest cycles depend on stump mortality and ability to resprout and cutting cycles of 10 to 30 years are indicated in the literature [83, 99, 104, 117].

Site selection is directly related to survival, growth, and yield of the tree species or clones. To obtain high productivities, sites should be of good quality with long growing seasons [83, 100, 101], and steep slopes should be avoided when mechanization is foreseen [99, 101, 104]. Control of natural vegetation to reduce competition between spontaneous vegetation and energy plantations is better suited during site preparation [101, 104, 115], though it might also be necessary after each harvest [93, 104, 123].

Two main options are available for the ***selection of planting techniques***: plantation of cuttings or seedlings. While the former is use with *Salix* spp. [101, 104, 124–126], the latter is chosen for *Populus* spp. or *Eucalyptus* spp. [101, 124, 126]. Similarly, two approaches are available for management: the plantation with a cut after 1 year in order to promote coppicing or first harvest at the end of the rotation length [93, 104, 121, 122].

Other management practices include fertilization to promote yield [93, 101], though there is some controversy in the literature, with some authors stating that fertilization does not increase yield (*e.g.*, [124, 126, 127]), while others state the opposite (*e.g.*, [128, 129]). The control of pathogens should be primordially done by choosing resistant species or clones or by the increasing diversity (*e.g.*, [101, 130]) and, if this is not enough, with phytopharmaceuticals [93, 98, 101, 115]. Irrigation should be used when water stress and growth reduction are expected [93, 131, 132].

4.2. Stands managed for timber and other products and services

The main goal for stands managed for timber and other products and services is not biomass for energy. The latter is a secondary production, composed of residues, which are growing stock unused parts, such as tops, limbs, stems, stumps, and that result from harvest (cuttings or late thinnings) or silvicultural practices (noncommercial or early thinnings) [8, 133]. Regarding forest residues, two management options can be considered: their maintenance in the stand to preserve or improve stand productivity and site fertility or their removal when negative impacts are not expected [134–136]. The amount of forest residues depends on the species, stand structure, and stem quality, which generate a wide variability on their quantity (*e.g.*, [8, 89, 137]). Two constraints should be considered: the proportion of residues that is feasible to remove from a stand, which depends on its spatial distribution, 50% when scattered and 65% when stacked [8, 138]; and the distance between the stands and the places where it will be used, a 20–50 km radius is frequently used [8, 88, 137, 139].

Considering the different stand structures, the ones that potentially originate larger amounts of forest residues are even-aged, mixed managed stands, where some species are not well suited for timber or with timber of bad quality, and pure or mixed unmanaged stands, with high density, individuals of small diameter and bad timber quality [8]. Noteworthy are also the agroforestry systems, where the forest portfolio can include energy plantations [140, 141] and stands managed for timber and other nonwoody products and services from which forest residues can be obtained [140, 142–144]. The latter, frequently in rather small quantities, are mainly derived from thinnings and prunings but also from sanitary cuttings or trees that have reached the end of their lifetime cycle [142, 144, 145].

5. Uses of forest biomass for energy

One of the advantages of biomass over other renewable energy sources is its versatility. Biomass in general, and forest biomass in particular, can be converted into electricity, heat, or transportation fuels. In practice, though, forest biomass is mainly used for heat and electricity production. The transformation of forest biomass into biofuels that can be used in the transport sector still faces various challenges, which have hindered its commercialization [146, 147].

5.1. Current status

Despite its advantages and despite being the most used renewable energy source, the current share of bioenergy in the world is still very limited. In 2015, bioenergy and renewable wastes accounted for 9.4% of the world's energy supply [2]. Among the various biomass sources, solid biofuels accounted for 63.7% of the global renewables supply (liquid biofuels, biogas, and renewable municipal waste accounted respectively for 4.3, 1.7, and 0.9% and the other renewable energy sources for the rest) [2]. In OECD countries, where biomass is mostly used in modern systems, the share of biomass and renewable wastes is even lower, with these fuels accounting for 5.2% of the total primary energy supply in 2015 and solid biomass accounting for 36.1% of the renewable energy supply [2].

Solid biofuels, which are almost entirely composed of wood, wood residues, and wood fuels, are used to produce electricity and heat. Direct heat is by far the most common application of solid biomass. In this case, biomass is used directly by the end users (*e.g.*, residential, industrial, commercial, agriculture) and not by the energy transformation sector (*e.g.*, power plants, combined heat and power (CHP) plants or heating plants). The dominance of the use of solid biomass for heating applications is mostly justified by its traditional use in the African and Asian countries for heating and cooking [1].

Looking at the situation in Europe, where biomass is mostly used in a modern way, the utilization of solid biomass by the energy transformation sector has a bigger prevalence. Power plants for the production of electricity have a 9% share, CHP plants both for the production of electricity and heat 16% and district heating plants 5% [148]. In total, the European energy transformation sector accounts for 30% of the solid biomass consumption, contrasting with the world average, which is around 9%.

5.2. Feedstock characterization

Biomass for energy uses comes from various sources. Generically, it can be divided into forest, agricultural, and residual biomass. From these three categories, biomass from forestry is by far the most significant source of biomass for energy production. In 2014, it generated more than 87% of the world biomass feedstock, while agriculture contributed with 10% and municipal solid wastes and landfill gas with 3% [1].

	Eucalyptus wood	**Poplar wood**	**Willow wood**	**Beech wood**	**Bark (pine)**	**Wood chips (pine)**	**Pellets (wood)**
Proximate Analysis (wt% dry)							
Fixed carbon	18.80	13.05	13.73	14.53	26.60	19.40	12.65
Volatile matter	80.40	80.99	73.18	84.87	71.80	80.00	83.64
Ash	0.80	1.16	1.68	0.60	1.60	0.60	3.71
Ultimate Analysis (wt% dry)							
Carbon	51.20	47.05	43.06	49.38	53.90	51.80	49.12
Hydrogen	6.00	5.71	5.49	6.17	5.80	6.10	7.82
Oxygen	41.69	41.00	38.36	43.55	38.26	41.19	38.77
Nitrogen	0.20	0.22	0.44	0.28	0.40	0.30	0.56
Sulfur	0.02	0.05	0.00	0.01	0.03	0.01	0.02
Moisture content (wt%, on wet base, as received)	4.00	4.80	11.40	15.20	5.00	3.87	4.70
LHV (MJ kg^{-1}) (dry)	18.50	18.19	18.05	17.97	20.10	19.56	17.42

Table 1. Forest biomass fuel properties [153].

Biomass from the forest sector (*e.g.*, fuelwood, forest residues, and wood industry residues) is mostly used as raw material and not subjected to an upgrading process. However, the use of upgraded biomass has been gaining importance and, for example, pellets are one of the fastest growing bioenergy carriers [1]. Some advantages of upgraded forest biomass over raw biomass are the fact that it is more uniform and convenient to use and especially well suited when biomass is consumed in a place far away from its production site. As a disadvantage it has a higher cost compared to the correspondent raw biomass fuel [149].

The most relevant properties in terms of energy conversion for some forest biomass fuels are presented in **Table 1**. Due to the variability for a specific species, they should be considered as illustrative. Untreated wood is characterized by low carbon content and high volatile matter and oxygen contents when compared to solid fossil fuels. This leads to the lower heating values of wood, which in combination with its low density results in low values of energy density. The lower heating value of oven-dry wood of different species does not have a large variation [150]. However, in practice, in many applications wood is not oven-dried and contains a certain amount of water. Typically, fresh timber has a moisture content between 50 and 60%, while timber stored for a summer and for several years have, respectively, 23–35% and 15–25% water content [150]. The lower heating value of wood fuels is very dependent on the water content of the fuel. The more water content the wood has, the lower is its energy content. The ash content of wood is typically low [151], but it can be significantly higher in bark [152]. Additionally, the harvesting process can introduce inorganic materials in the feedstock.

5.3. Conversion technologies

Combustion is by far the most common way of converting forest biomass into energy [154]. It is performed in batch or continuous systems, depending on the scale, and to produce heat, power, or combined heat and power. The focus of this chapter is not on the traditional equipment to burn wood, but a review can be found, for example, in Ref. [155].

5.3.1. Heating applications

Depending of the scale, different combustion equipment can be used. In Europe, most of the biomass is burned in small-size units for ***household heating***, whose scale is typically of the order of a few kW_{th}. Equipment such as stoves, fireplaces, furnaces, and boilers are used to produce heat (a description can be found in [156, 157]). The most common fuels are firewood, wood pellets, and wood chips. The conversion efficiencies depend on the equipment. The traditional open fireplaces have efficiencies lower than 20% [158] and should not be considered a heating solution. At the high end of the range, wood pellet boilers can achieve efficiencies of more than 90% [159]. The scale of nondomestic applications is very variable and can go up to several MW_{th}. Heat can be produced in main activity heating plants or in industrial facilities. It is in Europe that most ***district heating*** is used [160]. Most of the biomass heat sold by the European energy sector comes from CHP plants. Biomass heat-only plants are important in small-scale district heating systems [161]. The combustion technologies used in district heating power plants are mainly fixed bed, bubbling fluidized bed, and circulating fluidized bed furnaces (a description can be found in [157, 162, 163]). Fixed-bed boilers are less efficient (60–90%) than fluidized bed boilers (75–92%) [164]; they present lower costs and are typically used for smaller capacities than fluidized bed boilers [157]. Heat distribution losses have to be taken into account to know the overall efficiency of district heating. Several parameters affect heat losses, such as linear heat density, pipe diameter, or temperature level [165]. In the industrial sector, ***process heat*** is typically generated by boilers, dryers, kilns, furnaces, and stoves. Wood and wood-upgraded fuels (*e.g.*, torrefied pellets and charcoal) can be burned to provide the broad spectrum of temperatures required by the industries [166]. For low and medium temperature process heat, mainly boilers are used, while for high temperature process heat, direct heat is supplied [167]. The equipment used for direct heating is very diversified and dependent on the process itself. For example, Ref. [168] and Ref. [169] describe the equipment used in the iron and steel industry, while Ref. [170] in the cement, lime, and magnesium oxide industries. The combustion technologies used for indirect process heating are similar to the ones used in district heating. The industries that use biomass for process heat generation are mainly those that generate biomass residues (*e.g.*, pulp and paper and the wood and wood products industries). An example of a sector that does not produce biomass residues but uses solid biomass for the partial substitution of fossil fuels is the cement industry [171].

5.3.2. Power applications

The primary combustion technologies used in biomass-fired power plants are similar to that of district heating and industrial plants with indirect heating applications: fixed and fluidized bed boilers. Additionally, pulverized combustion is also used; it is used as well in industrial applications, but not so commonly [157]. Pulverized biomass-fired boilers are very efficient but require a considerable amount of fuel pretreatment [172] when the biomass is not already generated in fine particles (*e.g.*, in sawmills or cork industry). As far as secondary technologies are concerned, today biomass-fired power plants are mostly based on steam turbines [173]. The electrical efficiencies of these plants depend on the size of the power plant and tend to be within the range of 18–33% (for installed capacities of 10 to 50 MW_e, respectively) [174]. Higher efficiencies in larger systems have been reported in the literature [172]. The size of biomass power plants is typically much smaller than that of fossil fuel power plants due to the restricted availability of local biomass sources and transport costs. Co-firing of wood and coal is a strategy to reduce greenhouse gas emissions, improving the overall efficiency of power plant with no need for a continuous supply of biomass [175]. It enables the advantages of the larger coal-fired power plants, while partially using a renewable energy source. Gasification of forest biomass into syngas followed by combustion of the syngas is an interesting alternative to combustion only systems, which offers higher efficiencies especially for smaller capacity power plants [176]. The most mature technology is gasification coupled with an internal combustion engine [177]. They are used in smaller systems than steam turbines [178].

5.3.3. CHP applications

Combined heat and power is the simultaneous generation of electricity and useful heat. It is a much more efficient way to burn forest biomass than biomass-fired power plants, since the overall efficiencies of CHP plants is much higher (global efficiencies above 85% can be achieved [179]). CHP biomass systems have an important application in industries that generate wood residues, such as the pulp and paper and wood industries [180, 181]. The other important CHP application is district heating plants [160]. CHP power plants for capacities above 2 MW_e are dominated by burning biomass in steam turbines (Rankine cycle) [182]. Steam turbines are a mature technology and applied in a wide range of powers. However, in small decentralized plants their electrical efficiency is low [159]. In this case, CHP plants should be operated in a heat-controlled mode with low power-to-heat ratios [159]. For systems smaller than 2 MW_e, the biomass CHP conversion technologies are not so well established [182]. In this power range, one of the commercial technologies available is the organic Rankine cycle (ORC). Its electric efficiency is relatively low, but the investment and maintenance costs are lower than that of the conventional Rankine cycles [183]. Another commercially available technology for small capacities is the steam piston engine [159]. Its nominal efficiency is comparable to that of steam turbines, having in efficiency little variation at partial load, contrary to steam turbines that have low part-load efficiencies [159]. Stirling engines are not commercially available yet [184]. They are a promising technology suitable for CHP plants below 100 kW_e and achieve relatively high electrical efficiencies [182]. From all the commercially available technologies for sizes below 2 MW_e, gasification is the one that presents higher efficiencies [182].

6. Conclusions

The primordial source of biomass for energy is derived from stands and forests. Due to the wide range of stand structures, the amounts of biomass available for energy are also quite variable. Higher quantities per unit area are attained in energy plantations. Pure or mixed even-aged high forests managed for timber potentially originate larger amounts of forest residues when compared with the other types of stands. The renewed interest of biomass as a source of energy brought about the challenge of its estimation. Remote sensing is a useful tool that enables a more cost-efficient evaluation and monitoring when compared with the forest inventory approach. Forest biomass is a very versatile renewable energy source, yet its share on the world energy supply is relatively small. It is mainly converted to energy in combustion systems used for heat generation, but CHP and electricity production are also common. For most applications, the use of raw biomass is adequate, but it might be necessary and/or more appropriate to upgrade it.

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Conflict of interest

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Chapter 4

Pretreatment of Crop Residues by Application of Microwave Heating and Alkaline Solution for Biofuel Processing: A Review

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Abstract

The effect of microwave-assisted alkaline pretreatments and enzymatic saccharification of lignocellulosic agricultural crop residues are reviewed. Pretreatment is a major step for the efficient and effective biochemical conversion of lignocellulosic biomass to biofuel. Microwave-assisted alkali pretreatment is one of the promising techniques used in the bioconversion of biomass into useful energy product. The advantages of microwave heating coupled with alkaline pretreatment include reduction of the process energy requirement, rapid and super heating, and low toxic compound formation. This chapter reviews recent microwave-assisted alkali pretreatment and enzymatic saccharification techniques on different agricultural residues highlighting lignocellulosic biomass treatments and reducing sugar yields, and recovery. In addition, compiled up-to-date research studies, development efforts and research findings related to microwave-assisted alkali, and enzymatic hydrolysis are provided.

Keywords: microwave, Lignocellulosic biomass, agricultural residues, enzymatic saccharification, glucose yield

1. Introduction

Lignocellulosic biomass feedstock is one potential source of renewable energy and considered as a non-food material (second-generation feedstock) [1]. Agricultural and forest residues as well as industrial and municipal solid wastes are made up of lignocellulosic components [2]. They are environmentally friendly with a carbon-neutral footprint when converted to renewable energy, compared to fossil energy sources such as crude oil, coal, and natural gas [3]. Lignocellulose biomass consists of cellulose, hemicellulose, and lignin. Both cellulose and hemicellulose are polysaccharides with cellulose being the main molecule utilized for ethanol production. Unlike cellulose, which comprises long unbranched fibrils entirely made up of glucose, hemicellulose is a branched polymer, and its polymer chains are shorter than those of cellulose which are described as water soluble because some sugar units are linked to the acetyl groups [4–6]. Lignin acts as a glue between hemicellulose and cellulose and still has some energy value, which can be converted to a variety of value-added products [7, 8].

The production of bioethanol from lignocellulosic biomass (crop residues and waste crops) has been estimated to be 422–491 billion liters per year, which is 16 times higher than global bioethanol production [9]. Bioethanol blend with gasoline (E5, E10, and E85) indicates greenhouse gas (GHG) emission advantage since bioethanol is less carbon-rich than gasoline [10, 11]. The lignocellulosic bioethanol process can be categorized into four steps: pretreatment, saccharification, fermentation, and product (ethanol) recovery [12, 13]. Pretreatment facilitates the breakdown of cell walls and internal tissues of the lignocellulosic biomass through physical, chemical, and biochemical conversion processes. This process involves the disruption and disintegration of recalcitrant structures to open channels for enzymatic reactions in the substrate [14–16]. According to the U.S. Department of Energy [17], the biomass process dramatically reduces dependence on crude oil, supports the use of diverse, domestic, and sustainable energy resources, provides a basis for bioindustry development in accelerating economic growth, and represents an effective strategy for reducing carbon emissions from energy production and consumption.

Recently, many research works have described pretreatment as the most expensive stage in bioethanol production considering challenges faced during the conversion process [18]. Pretreatment accelerates lignocellulosic solubilization, thereby improving enzymatic reactions in the material [12, 15, 16]. **Figure 1** shows a schematic of the effect of pretreatment on lignocellulosic biomass. An effective pretreatment technique is needed to liberate the cellulose from lignin, reduce cellulose crystallinity, and increase cellulose porosity [11]. Various pretreatment methods have been developed according to different research studies [3], but the choice of pretreatment technique for a raw material/feedstock is influenced by many factors. These include sugar recovery yield, low moisture content effectiveness, lignin recovery, required particle size, and low energy demand [20].

Pretreatment methods include microwave (MW)-assisted, dilute acid, alkali, steam explosion, ammonia fiber explosion (AFEX), lime, organic solvent, ionic liquids, and biological. A combination of these methods has also been studied, and some studies are still ongoing [3, 20]. Kumar et al. [21] and Merino-Perez et al. [22] presented advantages of pretreatment on lignocellulosic biomass such as (1) improved substrates sugar formation, (2) avoid degradation of carbohydrate, (3) avoid the generation of toxic compounds that can inhibit hydrolysis and fermentation processes, (4) avoid the decomposition of cellulose and hemicellulose, (5) reduction in the number and quantity of chemical reagents used, and (6) cost-effectiveness. Many research reports have compared various pretreatment methods of lignocellulosic biomass, indicating advantages and disadvantages of each pretreatment method. However, the choice

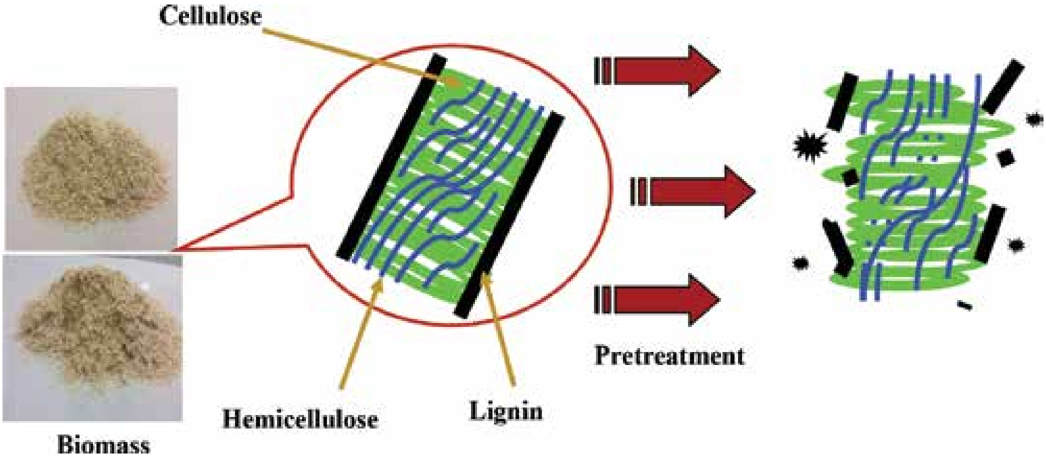

Figure 1. Effect of pretreatment on biomass [19].

of each pretreatment technique depends on the type of biomass, composition, and resulting byproducts [23, 24]. In addition, most of the pretreatment techniques suffer relatively low sugar yields, severe reaction conditions, high processing costs and capital investment, and investment risk [25]. Research efforts are continuing to address these challenges. For instance, there is growing interest in microwave heating as a pretreatment alternative to support second-generation lignocellulosic biorefineries. According to Aguilar-Reynosa et al. [18], microwave heating process has attracted a series of experimental techniques because it satisfies green chemistry, reduction of time of processing by 10 times compared to other heating techniques, fast heat transfer, and essentially an alternative method to conventional heating [26–28].

This review is intended to identify the various microwave-assisted alkali pretreatment effects on the different lignocellulosic agricultural residues. Emphasis is also placed on the pretreatment process effects of the lignocellulosic biomass and its sugar yield/recovery from enzymatic saccharification.

2. Microwave heating effects

Microwave (MW) irradiation refers to electromagnetic waves that consist of electric and magnetic fields. The waves are formed within a frequency band of 300 MHz and 300 GHz [29, 30]. The operational frequency of a domestic microwave oven is 2450 MHz and its heating mechanism with a material depends on shape, size, dielectric constant, and the nature of the microwave equipment. The heating mechanism in MW is aligned with dipolar polarization, conduction, and interfacial polarization. The alignment of polar molecules in an electromagnetic wave with rapid oscillation caused by microwave irradiation forces the polar molecules to align in the radiation field. Dipolar polarization is responsible for the continuous alignment of the polar molecules inside the material which generates the heat [30, 31]. Motasemi and

Afzal [32] and Xu [31] described three ways in which MW irradiation and materials can interact, namely (1) MW-transparent material (insulator) where microwaves pass through without losses like Teflon™ or quartz, (2) conducting material which cannot allow microwave penetration but reflected like metals, and (3) absorbing materials such as oil and water. The electromagnetic radiation in MW heating is shaped like energy propagating in a vacuum without any material in motion, can be observed as light, and used as waves and non-ionizing waves in mobile cell phones and infrared [33].

In 1949, Spencer Percy discovered that electromagnetic frequency radiation could be used in dielectric heating via microwave for heating application in food and other process requiring the use of heat. Von Hippel in 1954 provided further elaboration based on understanding of theories on macroscopic interactions of microwave and matters explaining his theory with dissipated power, electric field intensity, and propagation constant [18]. MW heating is directly from inside the material—wave interactions, leading to heat transfer and basically has a higher energy yield in comparison with conventional oven techniques which transmit heat by conduction-convention mechanism [34]. Xu [31] stated that conventional heating is transferred from the surface toward the center of the material by conduction, convention, and radiation; however, MW heating converts electromagnetic energy into thermal energy.

Numerous research studies have reported advantages and disadvantages of MW relative to conventional heating [18]. Advantages of MW include shorter residence time, faster heat transfer, selective, instantaneous on and off operation, precise and controlled heating, rapid and efficient, and environmental friendly process [4]. Due to its efficient process, MW heating has limited disadvantages such as (1) poor distribution of MW power within the material because of non-homogeneous material, (2) non-uniform heating, and (3) low penetration of radiation in bulk materials [35–37].

2.1. Alkali pretreatment of lignocellulosic biomass

Alkaline pretreatment improves cellulose digestibility, the ability to saponify intermolecular ester bonds, cross-linking xylan hemicelluloses, and other components. The effect of alkali pretreatment on lignocellulosic biomass is dependent on lignin content [20]. Alkaline reagents suitable for alkali pretreatment are NaOH, KOH, $Ca(OH)_2$, and NH_4OH. The sugar yield of alkali pretreatment is dependent on the feedstock used [3]. Some of the alkalis cause swelling, an increase in cellulose internal surface area, decreasing the degree of polymerization and crystallinity [38], while some disrupt the lignin structure of the material and remove acetyl groups from hemicellulose, thereby enhancing cellulose digestibility and increasing the reactivity of the remaining polysaccharides during delignification [12, 15, 22]. The advantages of alkali pretreatment are no washing of samples after pretreatment, no corrosion problem in the equipment used for the treatment as compared to acid, and the use of lower temperatures and pressures compared with other pretreatment techniques [39, 40].

2.2. Microwave-assisted alkali pretreatment technology and enzymatic saccharification

Ethanol from cellulose-based biomass is one of the most attractive alternatives to replace fossil fuels because using non-edible material as feedstock to produce ethanol and corresponding bioproducts minimizes environmental challenges [7, 22]. Microwave pretreatment method is a physico-chemical process involving thermal and non-thermal effects. The early discoveries of microwave pretreatment on lignocellulosic biomass were reported by Ooshima et al. [41] and Azuma et al. [42]. Since then, the technology has shown efficient applications in various ways [43–45]. Recently, many research studies have used MW heating as a pretreatment technique to assist in converting lignocellulosic biomass into useful bioproducts [46]. MW pretreatment combines both thermal and non-thermal effects within the aqueous environment of physical, chemical, or biological reactions [47], and its thermal heating may considerably decrease the time and efficiency of the pretreatment [22]. The pretreatment of lignocellulosic biomass using MW heating is done selectively especially at the polar parts, resulting in an increase in the disruption of the recalcitrant structures of the biomass [48]. To date, different pretreatment techniques to make lignocellulose accessible to enzymes for enhancing bioethanol conversion have been widely studied [20]. On the other hand, energy utilization in the pretreatment process raises the overall cost of producing bioethanol considerably, and this is a critical factor to consider before investing in biorefinery processes [20]. Darji et al. [49] and Aguilar-Reynosa et al. [18] reported the different studies on MW heating process describing MW heating as a better technology with energy efficiency to reduce energy consumption during pretreatment.

Enzymatic saccharification is a biochemical conversion preceded by pretreatment and followed by microbial catalyst conversion [50]. This is a microbial degradation process, accomplished by using enzymes and the result is usually a decrease in sugar [12]. Converting lignocellulosic biomass to ethanol involves disintegrating the biomass cell wall structure, thereby releasing the simple sugars which are fermented by yeast to produce ethanol [51]. Maitan-Alfenas et al. [52] reported that microorganisms are essential in enzyme production for lignocellulosic biomass saccharification. The saccharification process in the ethanol conversion requires less energy and is done in mild conditions at pH of 5.2–6.2 and a temperature range of 45–50°C [53, 54]. There are three distinct major types of cellulase enzymes used in the process: (1) endoglucanases (E C 3.2.1.4) hydrolyze at random internal β-1, 4-glucosidic linkages in the cellulose chain producing oligosaccharides of different lengths and with a shorter chain appearance; (2) exoglucanases of cellobiohydrolases (E C 3.2.1.91) progress along cellulose chain ends and release major products as cellulose or glucose; and (3) β-glucosidases known as β-glucoside glucohydrolases (E C 3.2.1.21) hydrolyze cellulose to glucose, liberate cellobiose, soluble cellodextrins to glucose [12, 55]. For hemicellulases, hydrolysis of the hemicellulose fraction requires more complex group of enzymes, and endo-β-1, 4-xylanase enzyme is needed for the hydrolysis of xylana, the major polymer component in hemicelluloses [56, 57]. Cellulases and hemicellulases production involve many microorganisms such as filamentous fungi (*Trichoderma* spp. and *Aspergillus* spp. native or genetically modified). During saccharification process, one of the fungi lacks β-glucosidase activity (*Trichoderma*), and it is supplemented with *Aspergillus* spp. in enzymes blending to improve the conversion of lignocellulose to simple sugars [9, 52, 58, 59].

Related research investigations have reported different activities of enzymatic saccharification process with limiting factors on the lignocellulosic biomass such as moisture, available surface area, crystallinity of cellulose, degree of polymerization, and lignin content [8, 20, 60, 61]. Biomass formed in a complex network of lignocellulose contents has indicated that most enzymes used in process can be absorbed by resultant condensed lignin to reduced yield by nonspecific linkages of the enzymes [52]. In addition, Palonen et al. [62] reported that the hemicellulose removal increases the mean pore size of the biomass, thereby increasing the chances of cellulose to get hydrolyzed. Consequently, lignin content reduces enzymatic saccharification by forming a shield and blocking substrate digestible parts from hydrolyzing [60]. Janker-Obermeier et al. [63] studied solubilization of hemicellulose and lignin from wheat straw through MW-assisted alkali treatment. The result suggested that more than 80% hemicellulose and 90% lignin could be removed from the solid wheat straw substrate without excessive saccharide solubilizing high amount of cellulose.

The combination of MW-assisted pretreatment and chemical pretreatment on different biomass as reported by several research studies indicated a higher sugar recovery, and various chemicals used in this process are dilute ammonia, iron-chloride and the common ones, alkaline and acid. All these chemicals assist MW pretreatment technology in removing lignin (alkali solution) and hemicellulose (acid solution) for cellulose accessibility [47]. The combined process separates lignocellulosic biomass components by disrupting the biomass structure, reducing the crystallinity of cellulose, improving the formation of fermentable sugars, and reducing the degradation of carbohydrates [64]. At lower temperatures, the combined pretreatment of lignocellulosic biomass improves enzymatic saccharification by accelerating the pretreatment reaction [65–67]. A combination of acid (H_2SO_4, 2% w/v) and steam (140°C, 30 min) is reported to have efficiently solubilized the hemicellulose, resulting in 96% yield of pentose in pretreatment and enzymatic hydrolysis of soybean hull [68]. Consequently, more research studies on MW pretreatment technique are still ongoing using different feedstocks and chemical combinations.

2.3. Effect of microwave power, alkali concentration, and residence time on enzyme digestibility

MW-assisted alkali pretreatment can penetrate the biomass and vibrate the molecules. The rapid oscillation of the molecules causes continuous heat generation and disruption of lignocellulosic structure, and similar results were reported by Hamzah et al. [69] and Wang et al. [70]. **Table 1** describes the effect of microwave-assisted alkali technology in enhancing enzymatic saccharification. Lignocellulosic biomass conversion to bioethanol is very challenging considering the heterogeneous nature of the feedstock used in the process [22]. MW pretreatment process leads to a high lignin removal and improvement in the biomass morphology to facilitate the reactivity of the enzyme, thereby increasing sugar yields [22, 79]. Increasing the alkali concentration during pretreatment of lignocellulosic biomass helps to increase cellulose digestibility and is more effective for lignin solubilization [3, 48]; a relatively long residence time is needed to produce high sugar yields at a lower temperature for alkali pretreatment technique [3]. Increasing NaOH solutions (2–5 wt%) with high temperature (60–140°C) and residence time (10–60 min) at a fixed MW power level of 500 W dissolves a high amount of hemicellulose in the supernatant. Xylan recovery was 73%, and solubilization of lignin was highly dependent on the MW energy input [63]. Xu [31] reported that MW irradiation is an effective heat source employed in alkali pretreatment to produce temperature needed in the delignification of biomass for enzyme reactivity. However, MW-assisted alkali

Biomass	**MW power (W)**	**MW time (min)**	**Alkali solution (%w/v)**	**Enzymes**	**Sugar analysis method**	**Sugar yield (dry biomass)**	**Reference**
Oil palm empty fruit bunch (EFB)	180	3–21	NaOH	*Trichoderma reesei* and β-glucosidase	DNS	178 mg	[11]
Switchgrass and Coastal Bermudagrass	250	5–20	NaOH, Na_2CO_3 and Ca $(OH)_2$	*Trichoderma reesei* and β-glucosidase	DNS	2% NaOH/10 min: 82 and 63% glucose and xylose 1% NaOH/10 min: 87 and 59% glucose and xylose	[44]
Corn straw and rice husk	1300	2	Glycerol-water and glycerol-NaOH	*M. heterothallica* and cellulase Celluclast	DNS	Glycerol-NaOH: highest sugar yield for both samples	[71]
Switchgrass	1000 (Setting #1 to #4)	30–120 s	NaOH and water	Celluclast 1.5-L and Novozyme 188	NREL	0.1 g/g NaOH/30 min: 58.7 g/100 g Water/MW: 34.5 g/100 g	[66]
Sugarcane bagasse	100, 180, 300, 450, 600, and 850	1–30	NaOH and H_2SO_4	Commercial cellulase	DNS	MW-alkali/600 W/4 min: 0.665 g/g MW-acid/100 W/30 min: 0.249 g/g MW-alkali (1%)-acid (1%): 0.83 g/g	[72]
Sweet sorghum bagasse (SSB)	1000	2, 4, 6	Lime	Cellulase (ACCELLERASE 1500)	DNS	SSB/MW/no-lime: 65.1% SSB/MW/lime: 52.6%	[73]
Wheat straw ear	400, 700, 1000	5–15 (5 min interval)	NaOH	Cellubrix L	NREL	1000 W/15 min: 148.93 g/kg Untreated: 26.78 g/kg	[74]
Switchgrass	250	5–20 (5 min interval)	NaOH and H_2SO_4	*Trichoderma reesei* and β-glucosidase	DNS	NaOH/250 W/10 min: highest yield	[67]
Sweet sorghum juice	100–160°C (15°C interval)	60	Dilute ammonia	Spezyme CP and *Saccharomyces cerevisiae* (D_5A).	NREL	4.2 g glucose/10 g at low temperature and short MW time	[25]
Rice straw	70–700	1–5	NaOH	E-CLEAN, endo-1, 4-β-glucanase and EBLUC and β-glucosidase	DNS	MW-assisted alkali: 1334.79 μg/ml	[75]
Pineapple	170–510 (170 W interval)	5, 10, 20, 40, 60, 120, 180 s	NaOH	Cellulase	HPAEC-PAD	33.5% total sugar yield at 6.375 W/g for 5 s	[76]
Cashew apple bagasse	600 or 900	15 or 30	NaOH	Commercial celluclast and β-glucosidase	NREL	0.2 and 1.0 mol/L NaOH: 372 and 355 mg/g	[77]

Biomass	MW power (W)	MW time (min)	Alkali solution (%w/v)	Enzymes	Sugar analysis method	Sugar yield (dry biomass)	Reference
Canola straw and Oat hull	713	6–18 (3 min interval)	NaOH and KOH	*Trichoderma reesei* and β-glucosidase	DNS	Canola straw: 110.0 mg/g Oat hull: 99.10 mg/g	[3]
Catalpa sawdust	200, 400, 600	3, 6, 9	MW-water, NaOH and $Ca(OH)_2$	Commercial cellulase	DNS	MW/$Ca(OH)_2$/400 W/ 6 min: 402.73 mg/g	[78]

HPAEC-PAD: high-performance anion exchange chromatography-pulsed amperometric detector; DNS: dinitrosalicylic acid; NREL: National Renewable Energy Laboratory

Table 1. Summary effect of microwave power, residence time, and alkali concentration in improving enzymatic digestibility in selected agricultural crop residues.

pretreatment technology is effective depending on the lignin content of the feedstock and can lead to a high lignin solubilization and increased sugar yields [52]. According to Chaturvedi and Verma [79], results from reducing sugar yields ranging from 40 to 60% are mostly reported from MW-assisted pretreatments. The review pointed out that no pretreatment technology offers 100% conversion of biomass into fermentable sugars. To obtain the optimal MW-assisted alkali pretreatment condition that can improve enzymatic digestibility using different biomass, various microwave power levels, residence times, and alkali solutions of various concentrations were considered. Also, feedstock properties and reaction conditions are contributing factors influencing microwave pretreatment characterization and yield of the final product.

The results from **Table 1** indicate that MW-assisted alkali pretreatment can enhance the acceleration of enzymatic hydrolysis process compared to the conventional method as reported by many research studies. Sodium hydroxide (NaOH) solution identified as the most widely applied in MW pretreatment process and effective alkali compared to other alkalis. It was observed that NaOH, residence time, and substrate concentration were the main factors affecting the enzymatic saccharification efficiency. From the different MW-assisted alkali pretreatment processes, a low MW power (200–400 W) and a short exposure time (1–25 min) of feedstock reactor improved enzymatic saccharification sugar yields. However, lime was not a good alkali reagent for MW pretreatment and enzymatic saccharification of sweet sorghum bagasse, whereas sodium and ammonium hydroxides were excellent with MW pretreatment and enzymatic saccharification in high yields of sugars depending on the biomass used.

Figure 2 shows the various sugar analysis methods applied in the last decade in quantifying the sugar yields from MW-assisted alkali pretreatment and enzymatic hydrolysis process of cellulosic biomass. The most widely applied method is DNS with 67% followed by NREL protocol with 28% over the last 10 years as indicated in the published research papers. None of the research studies that have used these methods indicated the most appropriate method. Rather, results of sugar yields were based on the type of biomass used and pretreatment parameters. However, there was no analysis on the cost of using any of the sugar analysis methods reported in the study.

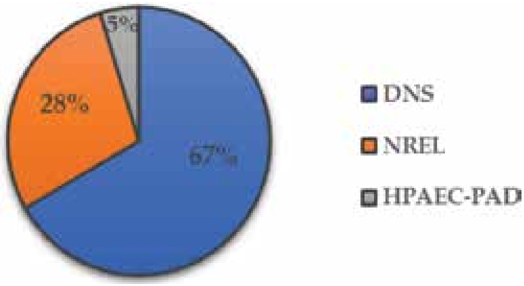

Figure 2. Cellulosic sugar analysis methods.

On the other hand, an overview of key pretreatment processes employed for the bioconversion of lignocellulosic biomass was reported by Chaturvedi and Verma [79]. The study suggested that alkali pretreatment process involving lime, ammonia, NaOH, and KOH resulted in higher yields of sugars involving lignocellulosic biomass with a low lignin content like rice hull and grasses. But concerns with environment challenges were associated with ammonia because it is toxic to the environment.

2.4. Effect of biomass pelleting on enzymatic digestibility

Densification of biomass is primarily achieved by pelletizing which is the application of mechanical force to compact biomass into uniformly sized solid particles [80, 81]. Densification increases the density of biomass into a pellet product having a density of 600–1200 kg/m^3 [82] for efficient transportation and low moisture for safe storage [83]. Particle size and preconditioning of biomass prior to pelletization can facilitate the binding characteristics and chemical composition of biomass, thereby improving the overall pellet quality [84]. In addition, moisture content as a factor during preheating of biomass before pelleting assists in loosening the natural binders to produce durable pellets [85].

The pretreatment process helps to complete biomass conversion into valuable bioproducts. Therefore, the pretreatment of lignocellulosic biomass is important in enhancing enzymatic cellulosic digestibility to increase glucose yields [86]. There is only one cited paper on the effects of MW-assisted alkali pretreatment and densification on improving enzymatic saccharification of biomass conversion into ethanol. Sugar yields were reported to increase after MW-assisted alkali pretreatments of canola straw and oat hull pellets. Sodium hydroxide (NaOH) and potassium hydroxide (KOH) at various concentrations were used in the study. The authors highlighted that samples selected for cellulosic substrate analysis were based on parameters that describe pellet quality such as tensile strength, dimensional stability, and pellet density [3].

Table 2 shows MW-assisted alkali canola straw and oat hull pellet data and corresponding glucose yield results. The tensile strength, dimensional stability, and pellet density showed little or no significant effect on the sugar yields on canola straw and oat hull pellets. It is evident that samples ground in a 1.6-mm hammer mill screen size had a significant effect on the cellulosic enzymatic digestibility. **Table 2** shows data and results from Hoover et al. [85] and Shi et al. [87] which were compared. Hoover et al. [85] indicated that preheating AFEX-pretreated biomass pellets had no effect on sugar yield while the non-preheated pellet had a

Feedstock	Screen size (mm)	Alkali	Alkali concentration (%)	MW time (min)	Tensile strength (MPa)	Dimensional stability (%)	Pellet density (kg/m^3)	Average glucose yield (mg/g)
Canola straw	1.6	NaOH	1.5	18	2.31	0.79	1370.27	110.05
		KOH	1.5	6	3.78	0.83	1392.21	53.42
	3.2	NaOH	0.75	6	4.85	2.60	1324.75	55.78
		KOH	1.5	6	5.19	0.83	1382.62	96.77
Oat hull	1.6	NaOH	0.75	18	1.33	5.28	1221.99	99.10
		KOH	1.5	6	0.63	1.04	1185.69	97.53
	3.2	NaOH	0.75	6	1.23	1.68	1205.73	72.22
		KOH	1.5	18	1.17	5.95	1210.94	84.87

Table 2. MW-assisted alkali pretreated canola straw and oat hull pellets and glucose yields results [3].

greater effect on the sugar yield. Also, Shi et al. [87] reported that efficiency in the mixed feedstocks pretreatments and densification demonstrated significant effect on sugar yields. Many studies without MW-assisted alkali pretreatment method using pelletization on different biomass have reported similar sugar yield, considering the biomass used in the conversion. Furthermore, conclusions made from these studies focused more on the effects of pelletization parameters on improving enzymatic hydrolysis process for biomass sugar conversion [85, 87–91]. The advantages of densifying biomass using different technologies to produce pellets are to improve handling, storage, and transportation efficiencies [92].

2.5. Economic evaluation of microwave pretreatment process

Technoeconomic analysis (TEA) involves technologies, system, and production processes evaluation. Different technoeconomic studies have classified the analysis into two major groups such as technical (maintenance requirement and service life, operation and maintenance skill requirement, the ease of transportation and installation, processing capacities available, material, esthetic and inherent risk for a system or product process) and economic (capital and operating costs, biomass cost, and profit revenues) depending on the process technology used [93, 94]. The TEA report also assists in understanding and providing additional information to the economic viability via production cost and market price [94], and the profitability and sensitivity analysis of a product or a process [95, 96]. To perform technical and economic evaluation, various software with in-built analysis tool to estimate capital and operational costs have been developed by different software developers, and the choice of software is dependent on the project evaluation. The available commercial TEA software includes Super-Pro designer, PRO/II and DYNSIM, Aspen Plus HYSYS, DESIGN II, and CHEMCAD [93].

Life cycle assessment (LCA) involves the collection and evaluation of relevant input and output data of a product system including potential environment impacts within the process period [97]. Adams et al. [98] indicated that the main reason for using the LCA tool is to give a holistic view of the emissions and resource requirements of a product system. Also, the importance of LCA study is to analyze the impact on the environment, energy consumption, and economic viability [94, 99]. Azapagic and Stichnothe [100] reported that LCA can be translated into quantitative measures of sustainability such as environmental, social, and economic. Different types of International Standard Organization (ISO) documents have been developed for LCA standards in providing flexible methodology and enabling modification of analysis by meeting up the goal and scope of the study [94, 97]. In the setting of innovation targets, the major impacts of LCA can be identified using these intensive products: raw material, manufacturing, distribution, the use of intensive product such as automobiles and laser printers, and disposal-intensive product [94, 100]. Many software, tools, and databases have been developed to assist in data processing and calculation of LCAs. These include Athena, BEES 4.0, CMLCA, Ecolnvent, EMIS, GaBi, GEMIS, IdeMAT, REGIS, SimaPro, and Umberto [101]. Many software are in market and many more are disappearing each year due to the dynamic nature and availability of the software [94]. Patel et al. [102] studied the technoeconomic and life cycle assessment of lignocellulosic biomass thermochemical conversion technologies. The study stated that a lot of research works are only focusing attention on calculating the cost of one specific production chain product. It suggested more technoeconomic investigation on multiple processes of product co-generation. Mupondwa et al. [103] reported that bioenergy research investigations and developments in Canada for biomass pretreatments and conversions into bioproducts using different technologies have recently shown significant growth. However, the study highlighted that there are challenges in designing business models and commercial bioconversion pathways based on various biomass feedstocks available. Despite the varieties of research that have been conducted on microwave pretreatment technique, the growth of industrial application of microwave heating is limited globally. Xu [31] reported that most pretreatment experiments still take place in domestic MW ovens except for few modified MW reactors which are used by less than 30 companies globally on the pretreatment of various feedstocks. The study on the TEA of MW-assisted alkali pretreatment is not available except for TEA on MW torrefaction and pyrolysis of biomass. Even with TEA on MW torrefaction or pyrolysis published papers displayed, an extensive literature search still showed limited information on the economic evaluation on the processes. Therefore, the technoeconomics of MW-assisted alkali pretreatment of biomass needs to be evaluated using available data to determine economic viability of the process, and this will be one of the topics of research that our group will undertake.

3. Summary

MW pretreatment technique has gained research attention and its future is growing. In spite of this, it is still under bench-scale development. Sufficient data generated from previous and recent studies can be used to quantify the dielectric properties of input biomass and to design and develop a continuous MW-assisted pretreatment and enzymatic saccharification process unit for commercial scale-up. Feedstock properties and reaction conditions are the two factors influencing microwave pretreatment characterization and yield of the final product.

The cost of MW pretreatment process is the main determinant associated with the adoption of this technology. Emphasis on the capital and operating cost investment will improve the pretreatment technique and hydrolysis process, thereby reducing the cost of the final product (bioethanol). Future research studies in MW-assisted biological pretreatment in improving lignocellulosic biomass digestibility, and techno-economic analysis and life cycle impact assessment of the process need to be considered. The concept is to develop a more economic pretreatment and hydrolysis techniques that can be environmentally sustainable and accepted by the bioenergy industry.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 5

Hydro-Fractionation for Biomass Upgrading

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Additional information is available at the end of the chapter

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Abstract

Lignocellulosic biomass is mainly composed of three components including cellulose, hemicellulose, and lignin. A fractionation step is considered as one of the most important preliminary processes for the separation of these three components before their further utilization. Among different separation techniques, water-based pretreatments or hydro-fractionations including (a) subcritical water extraction, (b) supercritical water extraction, and (c) steam explosion have shown their promising advantages both in terms of separation efficiency and in terms of environmental friendliness. Several hydro-fractionation technologies have been developed during the last decade in which each fractionation process has different impacts on the compositional and structural features of biomass. The fractionation principle, current status, and their potential uses in the biorefinery for sugar-based chemical platform production are mainly discussed.

Keywords: lignocellulosic biomass, hydro-fractionation, subcritical water extraction, supercritical water extraction, steam explosion, bio-based product

1. Introduction

The fossil fuel demand from industrialization and domestic utilization has been continually rising, which is in contrast to the depleting supply of petroleum resources that leads to public concerns for the adequacy of long-term energy supply and also environmental issues due to greenhouse gases being drastically released. In addition, the expanding consumption of natural resources also drives the global community to force with economic problems. The replacement of supplies from fossil fuels, which is one of the challenging tasks, has been of intense concern. The use of alternative energy from renewable resources is a promising solution not only for long-term environment sustainability but also in economic aspects. Plant biomass including agricultural, forestry, herbaceous, and residue, which is a sufficiently abundant natural renewable resource, has been considered as a suitable alternative carbon source that can be converted into useful sustainable products and varieties of chemicals. Among these, the exploitation and utilization of biomass energy have motivated and attracted a great deal of interest from around the world due to a power opportunity to improve energy security, reduce the trade deficit, dramatically lower greenhouse gas emissions, and improve price stability [1]. Besides the advantages mentioned above, agricultural biomass such as crop residues are generated with large quantity annually, making them promising sources for further utilization due to their abundance, diversity, and low-cost. Therefore these potential biomass residues can play important roles as sustainable carbon sources.

The term "lignocellulosic agricultural residues" is used for describing all organic materials which are produced as by-products from harvesting and processing agricultural crops. Chemically, lignocellulosic agricultural residue can be generally regarded as being composed of three polymers including 40–50% of cellulose, which is a major component, 25–30% of hemicellulose, and 15–20% of lignin along with smaller amounts of pectin, protein, nitrogen compounds, and inorganic ingredients [1]. Crystalline and amorphous bundles of cellulose form a skeleton surrounded by the covalently linked matrix of hemicellulose and lignin [2]. These polymers are associated with each other in a hetero-matrix and varying relative compositions depending on the system, type, species, age, stage of growth, and even source of biomass, and they can be in the form of liquids, slurries, or solids. **Figure 1** displays three main components of lignocellulosic biomass.

According to **Figure 1**, each component of lignocellulosic biomass is described below.

Cellulose: the most enormously bountiful biopolymer in the world and the main source of the C6 sugar unit is a linear homo-polysaccharide of D-glucose linked together by β-(1, 4) glycosidic linkages, with cellobiose as the smallest repetitive unit. The long cellulose chains linked together with β-(1, 4) orientation results in the formation of intermolecular and intramolecular hydrogen and van der Waals bonds, which cause cellulose to be packed into microfibrils; they are fine structures bundled up together to form cellulose fibers with highly crystalline structure causing its stable properties, insoluble in water unless at high temperatures or with the presence of a catalyst, and are resistant to enzyme attacks [1, 3].

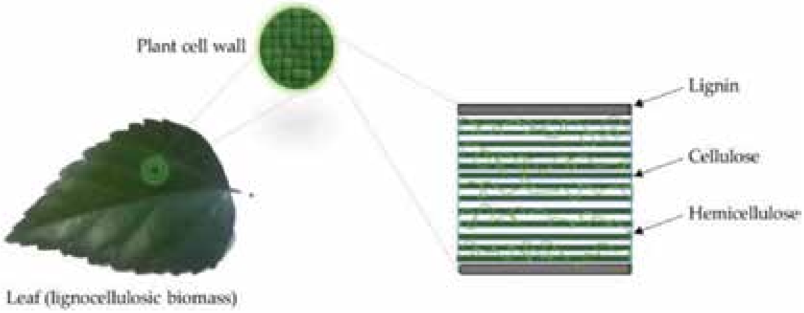

Figure 1. Lignocellulosic biomass composed of cellulose, hemicellulose, and lignin.

Hemicellulose: the second most abundant polymer is a complex, random, and amorphous branched carbohydrate comprising of different polysaccharides, including hexoses (D-glucose, D-mannose, D-galactose), pentoses (L-arabinose, D-xylose), and uronic acid with 50–200 units. The backbone of hemicellulose is either a homopolymer or a heteropolymer with short branches linked by β-(1, 4) glycosidic linkage or β-(1, 3) glycosidic linkage and groups of acetates were randomly attached with ester linkages to the hydroxyl groups of the sugar rings [3]. Hemicellulose has a lower molecular weight when compared to cellulose. Moreover, hemicellulose has short lateral chains, which provide linkage between cellulose and lignin, making hemicellulose easier to hydrolyze and degrade into monosaccharides than cellulose [4]. This allows hemicellulose to be removed under mild reaction conditions.

Lignin: it is a complex hydrophobic, large molecular structure containing cross-linked heteropolymers of three different main phenolic components which are trans-p-coumaryl alcohol, trans-coniferyl alcohol, and trans-sinapyl alcohol, which shield the polysaccharide fibers from external environment stress, microbial attacks, and oxidative stress. Lignin is recognized as the cellular glue and encrusting material due to the existence of strong carbon—carbon bond connection (C—C) and ether linkages (C—O—C), which together provide compressive strength to different compositions and individual fibers of lignocellulosic biomass (**Figure 2**).

The high crystallization region, high degree of polymerization, different connection forces between each composition, the protection effect from hemicellulose, and lignin of the lignocellulosic agricultural residue cell wall are stable and make it hard to be degraded for utilization in a further step; therefore, to convert lignocellulosic agricultural residue to biofuels, energy, or chemical platforms, a large number of pretreatment approaches have been investigated on a wide variety of feedstocks to deconstruct and fractionate the complex network structure to its simpler molecules in order to increase the efficiency of biomass composition utilization. Several fractionation technologies have been developed during the last decades. Those methods are usually classified into physical, biological, chemical, and physicochemical pretreatments. The several key properties to take into consideration for low-cost and advanced pretreatment processes are (a) the large amount of yield and harvesting time of feedstock, (b) the large volume of accessible pretreated substrate, (c) less sugar degradation, (d) a minimum number of inhibitors generated after the reaction, (e) a reasonable size and cost of reactor, (f) less solid waste production, (g) effectiveness at low moisture content, and (h) the minimum heat and power requirement [5].

Considering the concerns above, the most cost-effective processes in the biomass upgrading in the industry utilize the dispensable pretreatment and fractionation process where water most

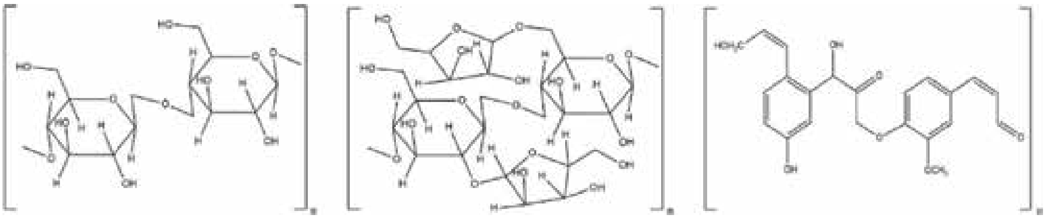

Figure 2. Examples of cellulose (left) hemicellulose (middle) and lignin (right) structures.

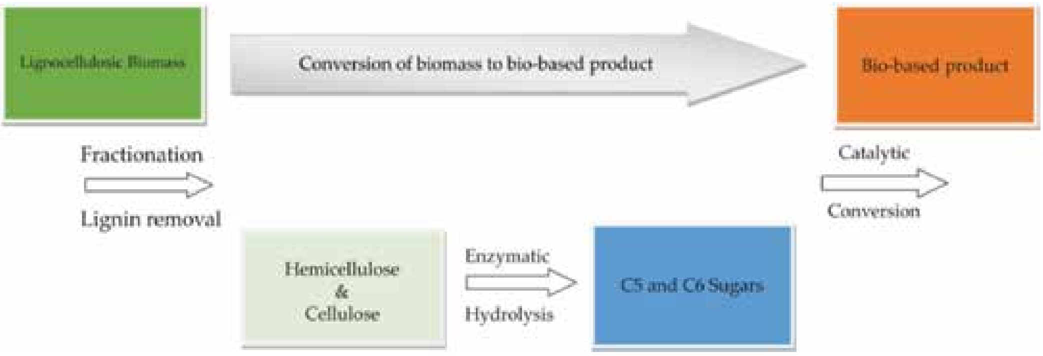

Figure 3. Process for sugar-based chemical platform production from biomass.

certainly takes great effects. The essential function of water in common fractionation includes the following: (a) it acts as a mass transfer medium, (b) it plays as a reactant constructing a mild acidic state due to the mitigation of pKw at an increased temperature, (c) it performs as a heat transfer medium, and (d) it represents as an explosion medium for explosion pretreatment to tear biomass into small pieces. Due to the advantages of water-lignocellulose interaction and efficacy, many attempts have practically focused on applying water into the fractionation process to separate the mixture of lignocellulosic biomass into an individual composition called aqueous fractionation, hydro-based fractionation, or "hydro-fractionation." The overall process of bio-based product production from lignocellulosic biomass is shown in **Figure 3**.

Hydro-fractionations or the processes utilizing water as a medium, reactant, or catalyst for separating mixture compositions including subcritical extraction, supercritical extraction, and steam explosion are mainly discussed in terms of their fractionation principle, current status and potential uses, life cycle and bioeconomy.

2. Principle of hydro-fractionation

2.1. Subcritical and supercritical water extraction

Subcritical and supercritical water extractions have been employed extensively in biomass utilization due to the tunable physical and chemical properties of water, potentially valuable products, and environmental friendliness. Furthermore, these two fractionation methods are known as the promising methods to make the biorefinery concept more practical with sufficient and sustainable profit.

Typically, subcritical water is defined as the use of water at a temperature between the boiling point and critical temperature (373–647 K) under pressure, which is high enough to maintain its liquid state. Supercritical water occurs at a temperature and pressure higher than its critical point (22.1 MPa and 647 K). In the supercritical region, the properties of liquid and vapor fuse [6, 7]. The behavior of subcritical and supercritical water near critical point mainly depends on pressure and temperature; therefore, some important properties of water could be tuned

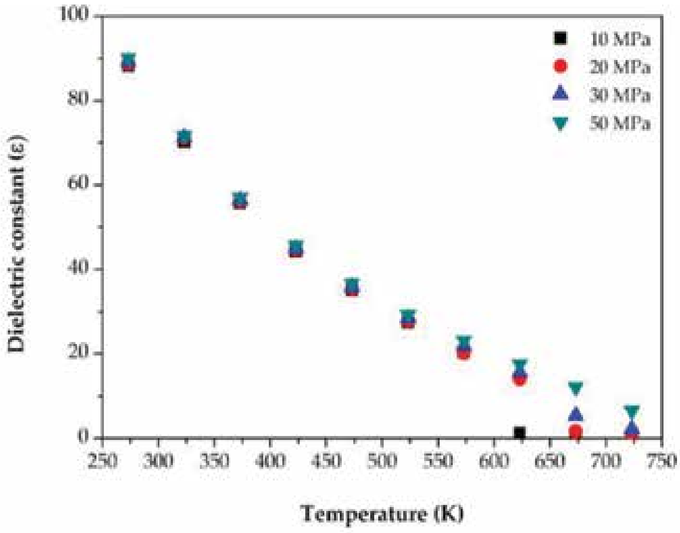

Figure 4. Static dielectric constant of water at various temperatures and pressures [14].

by varying the temperature and pressure for particular conditions of biomass fractionation. In this section, the important properties of water at the subcritical and supercritical state related to biomass fractionation including dielectric constant, ionization constant, density, and viscosity are demonstrated and discussed. A better understanding of water properties under various temperatures and pressures can allow an appropriate experimental design and suitable operating conditions for some specific proposes.

Dielectric constant is a dimensionless value showing the relative permittivity of a material compared with the permittivity of free space. Typically, the high dielectric constant of a solvent means that it has high polarity and vice versa. **Figure 4** shows the influence of temperature and pressure on the dielectric constant. The value of the dielectric constant tends to decrease with the increasing temperatures while it is slightly affected by pressure around the critical point. This phenomenon hints that the polarity of water can be reduced by increasing the temperature which indicated that the solubility of hydrophobic organic compounds and low molecular biopolymers in biomass could be enhanced by using low polarity of water generated at elevated temperatures [8–10]. It is worth mentioning that low polarity of water also reduces the solubility of salt in the process, especially type 2 salts (classified by solubility behavior) such as Na_2SO_4, Na_2CO_3, and K_2SO_4 [11], and the participation of salt might cause fouling that diminishes the efficiency of the process or even terminates the process. Therefore, the water supply should be treated to eliminate type 2 salts before its use in the process; also, a special design of a reactor might be required in case of raw material containing high contents of type 2 salts [12, 13].

The ionization constant of water is the ratio between the concentration of ionic ($[H_3O]^+$ and $[OH]^-$) products and the reactant at the equilibrium condition. The influence of temperature and pressure on the ionization constant is shown in **Figure 5**. In the subcritical region, the ionization constant increases with the raising of temperature and is slightly affected by the increase of pressure. On the other hand, beyond critical temperature, the ionic constant

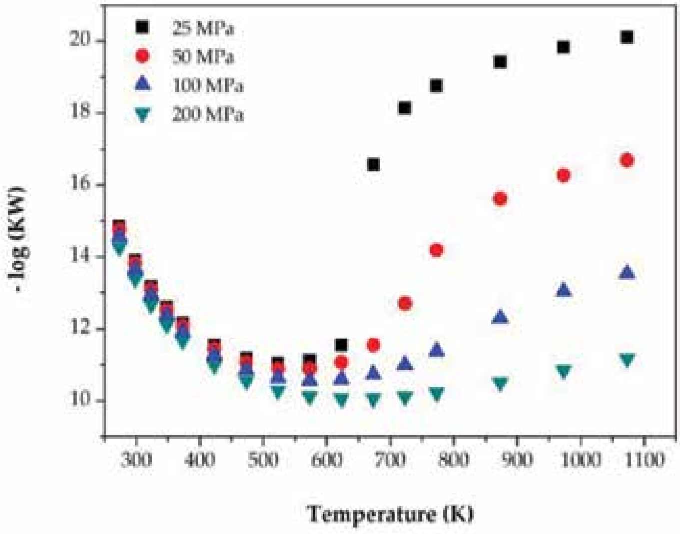

Figure 5. Negative log (base 10) of ionization constant of water at various temperatures and pressures [19].

declines with the increase of reaction temperature and dramatically drops with the reduction of pressure. Therefore, the reaction of biomass degradation takes place in ionic media for subcritical water extraction. On the other hand, the supercritical water extraction provided a radical-oriented environment for biomass fractionation [15–18].

Density of water is defined as the ratio between the mass and volume of water at a specific temperature and pressure. The density of water is decreased with the increase of temperature due to the expansion of the volume. With the increase of pressure, the density of water increases. The higher density of water at specific conditions provides a better chance to penetrate the biomass structure [20].

The viscosity of water is the resistance of water from the external stress such as tensile strength and shear strength. It refers to the resistivity of the water over movement or deformity. The viscosity of water decreased with the increase of temperature but only a slight change was observed when the pressure increased in the subcritical region. However, a more effect of higher pressure was found in the supercritical region on the higher value of viscosity. The viscosity has a direct effect on biomass fractionation. Since the small value of water viscosity provides better wettability of the biomass, the penetration of water to destroy the biomass structure increases (**Figure 6**).

2.2. Steam explosion

Steam explosion, one of the most widely employed hydrothermal technologies for pretreating lignocellulose in industrial applications to convert biomass into useful chemicals, has been recognized as an environmental friendly pretreatment method that can effectively enhance subsequent enzymatic hydrolysis without the necessity of using chemicals, except water, which can lower environmental impact, lower capital investment, bring more potential for energy efficiency, and give rise to less hazardous process chemicals and conditions; this offers several attractive features when compared to hydrolytic acid and oxidative processes. Steam explosion involves exposing wet lignocellulosic biomass to high-pressure saturated steam (0.69–4.83 MPa) and temperature

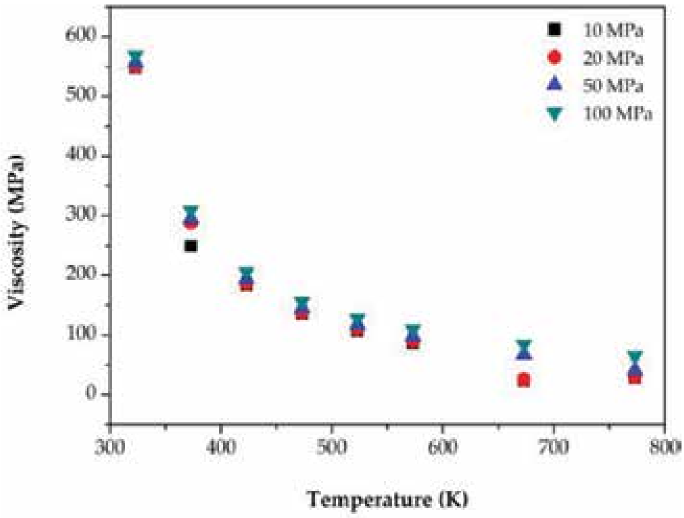

Figure 6. Viscosity of water at various temperatures and pressures [21].

(433–533 K) for a period ranging from seconds to several minutes and then suddenly depressurizing it to atmospheric pressure, making the biomass undergo an explosive decompression. This pretreatment is the combination of mechanical forces and chemical effects due to autohydrolysis of the acetyl group in hemicellulose. Autohydrolysis takes place from the formation of acetic acid from the acetyl group in the hemicellulose structure at high temperature where water acts as an acid at high temperature. The hemicellulose and lignin bonds are cleaved during the explosion, allowing the hemicellulose become water soluble; water-soluble lignin from plant cell wall is also released from the cleavage action into water phase. The mechanical effect is caused by explosive decompression that occurred from suddenly dropped pressure at the termination of the pretreatment, which induced the cell walls in biomass to undergo structural disruption and expansion. Because of these effects, a part of hemicellulose hydrolyzed and solubilized; lignin was redistributed, lignocellulosic matrix polymer was broken down, particle size was decreased, the degree of polymerization was reduced, and porosity was increased; moreover, cellulose was slightly depolymerized, which led to the improvement of lignocellulose digestibility [22–24].

Supercritical extraction in terms of operating conditions, reaction mechanism, and preferred biomass is shown in **Table 1**.

Hydro-fractionation method	Temperature range (K)	Pressure range (MPa)	Fractionation route	Application
Subcritical water extraction	373–647	>0.001 (maintain liquid phase)	Liquid ionic reaction	Extract desired product
Supercritical water extraction	>647	>22.1	Radical reaction	Extract desired product
Steam explosion	433–533	0.69–4.83	Rapid volume expansion of water	Reduce crystallinity of biopolymer

Table 1. Comparison of different hydro-fractionation methods.

3. Current status of hydro-fractionation

3.1. Patent filing of hydro-fractionation technologies

In **Figure 7**, it showed that numbers of filed patents in fields of subcritical and supercritical water extraction and steam explosion technologies have increased from 2007 to 2015. The trend of patent filing of subcritical water extraction decreased in 2016 and was the same number until 2017. On the other hand, more patents were filed in supercritical water extraction and steam explosion after 2015. Quantitatively, it can be seen that the number of filed patents for supercritical water extraction is a lot greater than that of steam explosion and subcritical water extraction. This could be explained by the fact that supercritical water extraction has more versatile applications than the other two technologies. Since this method is not only employed in biomass fractionation, it could be used in coal, oil, polymer, organic and inorganic compounds, nanomaterial, and waste-recycle applications [25].

3.2. Subcritical and supercritical water extraction

With the adjustable properties of water regarding operating temperatures and pressures described earlier, subcritical and supercritical water extraction were applied in many studies to resolve the complexity of the biomass structure. To achieve the maximum benefit from the utilization of biomass in the biorefinery, the conditions of the selective pretreatment of subcritical and supercritical water extraction were tuned. Therefore, several kinetics of selective products

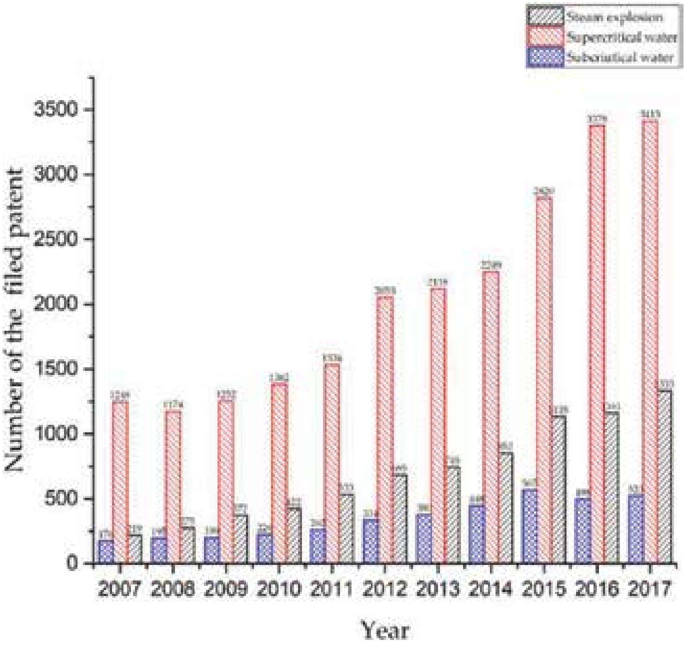

Figure 7. Numbers of filed patents in hydro-fractionation technology.

from the model compounds and the fine conditions including temperature, pressure, heating rate, and residence time were published [26–29]. It is worth mentioning that in subcritical extraction, temperature, heating rate, and residue time enormously affected the reaction behavior and desired products, while the role of pressure is to maintain water in a liquid state and increases the rate of reaction. On the other hand, the effect of pressure on the reaction and kinetics was gained at the supercritical water state [30]. The first component after the degradation of biomass under hot compressed water is hemicellulose at a temperature above 453 K. Typically, at a suitable temperature, a random cleavage between monomeric sugar bonds took place and hemicellulose oligomers were extracted when the chain was cleaved until shorter chains were obtained. And if the reaction time is high enough, another reaction called deacetylation occurred and gave acetic acid. With higher temperature, the product yield was increased but the selectivity dropped [31, 32]. Moreover, if the temperature was raised above 513 K, the oligomer of cellulose from the amorphous part in cellulose was generated, leading to the reduction of the solid yield [33]. After the temperature reached 553 K, the products derived from the hydrolysis reaction of cellulose were 5-hydroxymethylfurfural, levulinic acid, formic acid, and lactic acid [34–36]. For the extraction of lignin, there was a handful of evidence that indicated that the decomposition temperature of lignin without the addition of a catalyst was above 623 K and provided phenols, cresols, guaiacol, catechol, and methyl dehydroabietate as its degrading products [37, 38].

3.3. Steam explosion

The steam explosion process offers several attractive features for biomass fractionation technologies. Obviously, this process has low environmental impacts and mild operating reaction conditions, no chemical is required except water, and moist biomass can be used as feedstock; the higher the moisture content, the longer the steam pretreatment time [39]; it provides high sugar yield and small amounts of by-products and offers low capital investment. However, some unwanted degradation compounds occur when the operating condition is excessive (high temperature and pressure). For example, xylose obtained from hemicellulose could be degraded to furfural, and glucose obtained from cellulose could be degraded to 5-hydroxymethyl furfural, respectively. These two by-products are undesirable compounds since they could inhibit some microbial activities. Therefore, some detoxification methods should be determined prior to enzymatic hydrolysis. During the process, heat transfer can generate the issue of overcooking at the surface of the larger biomass particles and an incomplete pretreatment of the interior region [39], so optimization size of the feedstock is also a crucial step to achieve high sugar conversion and low production cost.

Steam explosion can be performed as a process either in a batch or as a continuous reaction with the most important operational conditions as residence time, temperature, and particle size; a combination effect of these parameters that depend upon feedstocks has been operational for steam explosion such as Salix [40], orange peel [41], wheat straw [42] and barley straw [39]. In recent years, there have been a good number of researchers who gained interest in the underlying work of water responsibility. Boluda-Aguilar et al. studied the steam explosion pretreatment of lemon (*Citrus limon* L.) citrus peel wastes to obtain bioethanol, galacturonic acid, and other coproducts [43]. The steam explosion pretreatment showed an interesting effect on lemon peel wastes for obtaining ethanol and galacturonic acid. The simultaneous saccharification and fermentation (SSF) processing of steam-exploded lemon citrus peel wastes with low enzymatic concentration produced more than 60 L ethanol/1000 kg of fresh lemon citrus peel wastes. In addition, it has been discussed that the minimum inhibitory concentration of lemon citrus essential oils on yeast is lower than that obtained from orange and mandarin citrus essential oils. Singh et al. [44] reported the steam explosion of sugarcane bagasse, which eventually showed the enzymatic hydrolysis efficiency of 100% after 24 h of incubation by using the cellulases from Penicillium pinophilum with an enzyme loading of 10 FPU/g. To compare its potential use with commercially available cellulose (Accellerase™ 1000), the results indicated that using Penicillium cellulase and Accellerase™ 1000 showed that the saccharification potentials are comparable to the treated substrates such as steam-exploded sugarcane bagasse and ball-milled cellulose powder.

In our recent report on sugar production from sugarcane bagasse, the batch-type steam explosion system was developed for lignin removal to increase sugar yield. The sugarcane bagasse was first impregnated in a diluted alkaline solution and subjected to the steam explosion experiment at the temperature range of 433–493 K with the pressure below 2 MPa for a maximum reaction time of 10 min. The study showed good synergy on the combination of diluted alkaline impregnation and steam explosion for enhancing the purity of obtained bagasse leading to the higher yield of sugar production after the enzymatic hydrolysis process [45]. This could be a good evidence to show that the combination of the steam explosion technique and diluted base solution treatment could fractionate the lignin content into the water phase and provide the nonsoluble solid product of cellulose and hemicellulose for sugar production.

4. Life cycle assessment and bioeconomy of biomass upgrading

4.1. Life cycle of biomass hydro-fractionation

For the conversion of the lignocellulosic biomass feedstock to bio-based products, there are several processes involved. Firstly, the agricultural plants are grown and harvested in which the agricultural residues and wastes could then be collected and transported for storage. The pretreatment and fractionation of the biomass are performed to prepare the material for some particular manufacturing processes. The obtained bio-based products are later on distributed to marketplaces and delivered to customers. The life cycle assessment (LCA) is known as a systematic method for evaluating the environmental impact of a product's entire life, starting from growing its feedstock to its disposal process [46]. For example, in case of the bio-based product, lignocellulosic biomass feedstock was generated from agricultural crops which require soil, fertilizers, water, and sunlight for its growth, while water, electricity, and heat are necessary for its manufacturing process. However, to make this chapter concise, only the pretreatment and fractionation process of the feedstock is emphasized.

In a study, Prasad and his team evaluated the life cycle of four different pretreatment methods including liquid hot water (or subcritical) extraction, organosolve extraction, dilute acid extraction, and steam explosion of milled corn stover [47]. The four environmental impacts in terms of climate change, eutrophication, water depletion, and acidification potential were predicted and compared among the four methods. For climate change, the CO_2 emission was reported whereas subcritical water extraction gave the smallest amount of CO_2 emission while almost 15 times of CO_2

could be released from steam explosion due to higher energy consumption which required more electricity during the fractionation process. The second parameter, eutrophication or the nutrition enrichment of the Earth's surface, was determined by comparing nitrogen gas and phosphorus equivalents. The eutrophication took place mostly on the feedstock growth step; therefore, the efficiency of the fractionation process plays important roles on this part. Subcritical water extraction was found to show the smallest impact on eutrophication since less amount of feedstock is required for producing the same amount of the desired product. The subcritical water extraction also showed the smallest impact toward water depletion. In addition, the study indicated more than 90% of water in all four processes that was used in the feedstock growth step. The last parameter is acidification potential, where organosolve extraction and steam explosion showed smallest effects while diluted acid extraction had the highest impact on acidification potential.

4.2. Bioeconomy of bio-based product manufacturing from biomass

Besides the environmental impact, an economic aspect is very important for product development. The term bioeconomy or bio-based economy refers to an economy employing renewable bioresources such as microorganisms, agricultural crops or residues, and livestock to produce food, pharmaceuticals, energy, plastics, and other bio-based materials. In this context the utilization of lignocellulosic biomass from agricultural residues for the production of various bio-based products was explained. As shown in **Figure 8**, promising products from biomass feedstock upgrading are biogas, biofuels, biochemicals, bioplastics, carbon fiber, nanofiber,

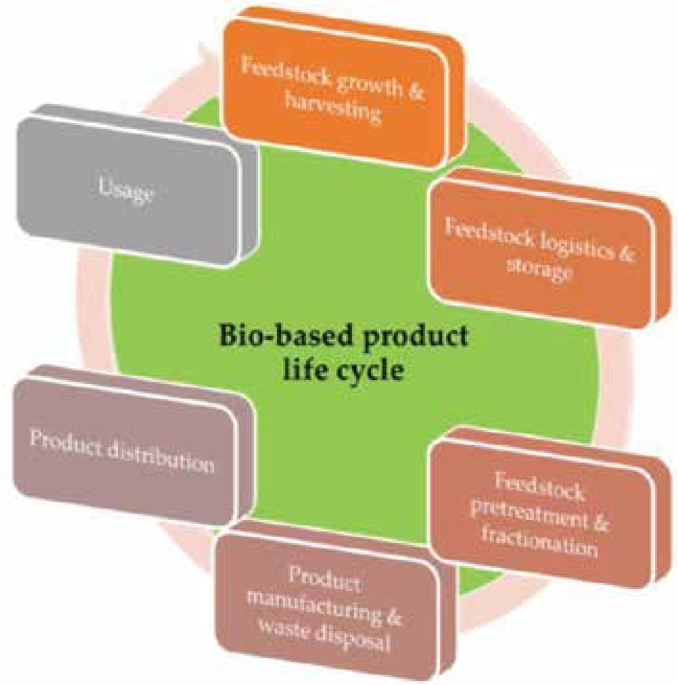

Figure 8. Life cycle of bio-based product upgraded from lignocellulosic biomass.

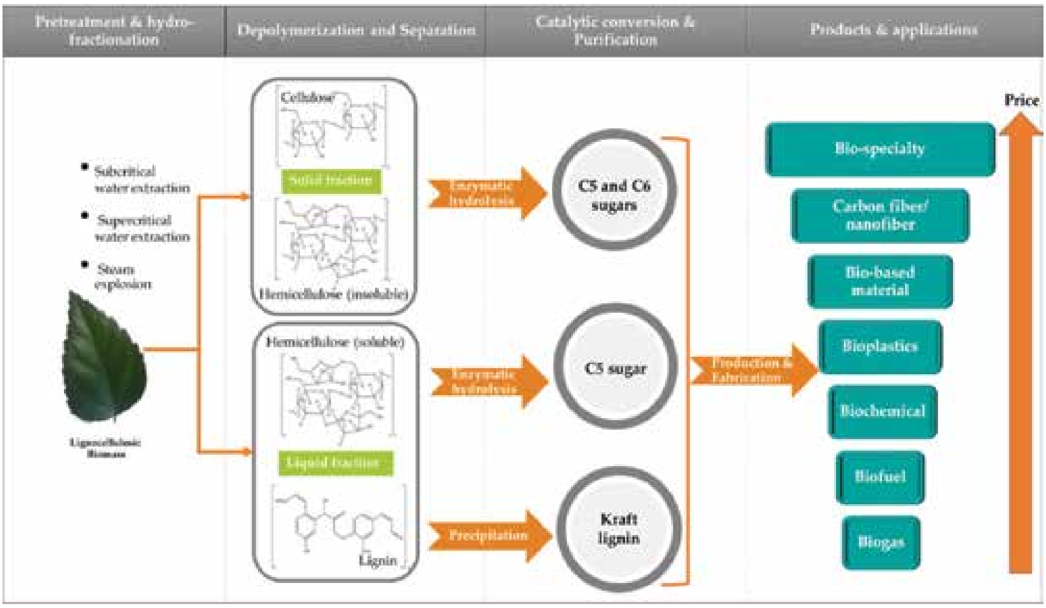

Figure 9. Bioeconomy of biomass upgrading.

and bio-specialty (a unique high-value product derived from bioresources for a specific customer group). In general, the feedstock undergoes pretreatment or hydro-fractionation to prepare the material for some particular applications. Then, the material is manufactured to produce a targeted product (**Figure 9**).

5. Conclusions

Hydro-fractionation enhanced lignin removal and provided a higher yield of sugar-based chemical platform production from biomass. The three green processes including subcritical water extraction, supercritical water extraction, and steam explosion are practical for biomass treatment. With the adjustable water properties, subcritical and supercritical water extractions are attractive tunable techniques for various bio-based compound extractions while the rapid volume expansion of water in steam explosion can destroy the high crystallinity of biopolymers. In addition, some technical feasibility in terms of energy consumption and reactor system as well as economic feasibility should be taken into consideration for future advancement.

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Chapter 6

Statistical Optimization of Acetoin Production Using Corn Steep Liquor as a Low-Cost Nitrogen Source by *Bacillus Subtilis* CICC 10025

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Additional information is available at the end of the chapter

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Abstract

This chapter investigates the effect of some selected nitrogen sources (corn steep liquor—CSL, yeast extract, and beef extract) on the bioproduction of a selected flavor—acetoin (AC) from glucose—with a view to optimize its production. The results revealed that by using a cheap nitrogen source, corn steep liquor, the yield of acetoin is similar to those of the extracts of yeast and beef. Furthermore, it was shown that by using the Box-Behnken design, the optimum parameters such as glucose concentration, corn steep liquor, and inoculum size to maximize the concentration of acetoin produced are 78.40 g/L, 15% w/v, and 2.70% v/v, respectively. The validated concentration of acetoin produced in a triplicate analysis, 10.70 g/L, was 0.06% less than the predicted value. The results of this study may encourage the development of cost-effective nutritional use of corn steep liquor for bioproduction of acetoin on an industrial scale.

Keywords: acetoin, bioproduction, corn steep liquor, statistical optimization, Box-Behnken design, response surface methodology

1. Introduction

The increasing trend in the consumption of healthy food and the growing demand of natural products by consumers coupled with the price margin between the synthetic and natural flavors have motivated the bioconversion of natural flavors like vanillin, acetoin (AC), etc. that is cost-effective and commercialized. Likewise, the new sustainable development goals of the united nation, goal 3 and 12 stated the need for the good health and well-being of the consumer and to ensure the sustainable production and consumption patterns of food product. Acetoin (3-hydroxy-2-butanone or acetylmethylcarbinol) is widely used in the food industry as a flavor enhancer, giving a buttery taste [1]. It can also be used as a building block for various chemicals such as alkyl pyrazines, diacetyl, and acetyl butanediol [1, 2]. Currently, most of the commercial acetoin is produced by chemical synthesis from 2,3-butanedione and 2,3-butanediol. However, the use of such chemically derived acetoin is restricted to food and cosmetic industries because of safety concerns [3]. The production of acetoin by microbial fermentation has been reported to gain increasing interest due to its safety and environmental friendliness [3, 4]. Intensive efforts have been taken to enhance microbial production of acetoin, including screening of high-yield acetoin-producing strains [5, 6], metabolic engineering breeding [7–9], and fermentation optimization [9–11]. The price of chemically generated acetoin (racemic) is over $ 16.2/kg, and biologically generated dietary acetoin can be two times more expensive [12]. One of the chemicals that can use acetoin as a building block is 1,3-butadiene (BD), which has a worldwide market of 11 Mt./year [13]. However, acetoin is only a minor by-product of 2,3-butanediol production, and its accumulation usually needs complex and expensive growth factors. Apart from carbon, which acts as feedstock for most fermentations, nitrogen is another significant nutrition compositional element needed for the active microbial growth for the fermentation of most targeted bioactive compounds [14].

Studies have shown the potential of low-cost media and complex nitrogen sources like urea, peptone, yeast extract, beef extract, soya bean [14–16] for acetoin production but yet to ascertain effectively the optimized condition. Nitrogen source is one of the main contributors in the total material cost of commercial acetoin production. Hence, replacing a costly nitrogen source with less expensive ones for acetoin production may improve the economics of the process. Corn steep liquor (CSL) has been identified as a potential nitrogen source in biochemical industries and a good substitute for other expensive complex media. It is a major by-product found during cornstarch processing. it is a low-cost source of proteins (**Figure 1**), amino acids, minerals, vitamins, and trace elements and can be used as a rich and effective

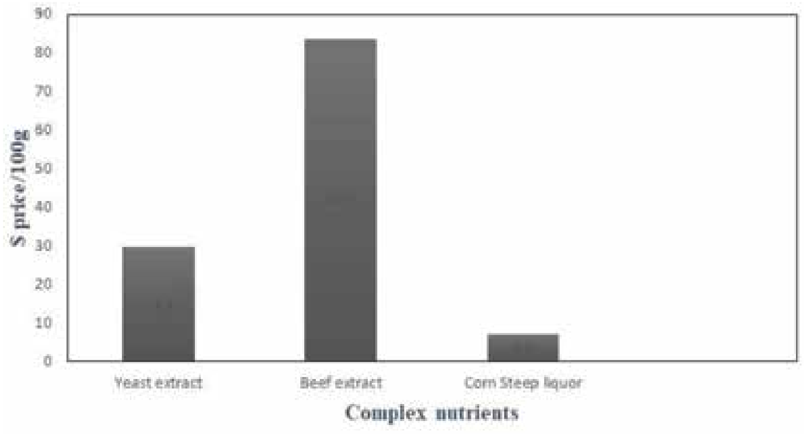

Figure 1. Graphical illustration of complex nitrogen nutrients and price margin.

nutritional substitute for expensive complex media like yeast extract, beef extract, and peptone in fermentations [17–20].

Studies have shown that CSL can be used as a nutrition supplement and a cheap nitrogen source for cellular growth in the production of some fermentation products [18, 20, 21]. Yang et al. [15] reported that when a high concentration of CSL was used in acetoin production, cell growth improved with a 3.69-fold increase in acetoin and an improved acetoin productivity [15]. Another author reported that a lower concentration of corn steep liquor had negative effects in the screening of medium components for acetoin production using a newly isolated *Paenibacillus polymyxa* CS 107 [2]. The work by Xu et al. [22] also confirms that CSL and yeast extract had a positive influence on acetoin when screened among other nitrogen sources. All these authors report differently on the optimized condition of CSL as nitrogen source and mostly combined its usage with other costly nutrients like yeast extract and beef extract. This necessitated the need for an optimizing tool like response surface methodology (RSM). Response surface methodology (RSM) is an empirical modeling technique used to establish the relationship between a set of controllable experimental factors and the observed results. RSM defines the effect of the independent variables, alone or in combination, in the processes. In addition to analyzing the effects of the independent variables, this methodology also generates a mathematical model [23]. The applicability of RSM to optimization studies has been demonstrated successfully [23–25]. This chapter focuses on the use of corn steep liquor as a cheap replacement for other expensive complex nutrients such that the CSL and other fermentation controlling parameters could be optimized, using RSM technique for acetoin production. The view of this study is to develop a low-cost fermentation medium that precludes redundant nutritional supplements and minimizes the costs associated with industrial acetoin fermentation.

2. Materials and methods

2.1. Microorganism and inoculum preparation

B. subtilis CICC 10025 purchased from the China Centre of Industrial Culture Collection was used in this study. It was maintained on agar slants with the following medium (g/L): glucose 10, beef extract 10, peptone 10, sodium chloride 5, and agar 16 at pH 7.0. The seed culture was prepared by growing the bacterium in 50 ml of the following medium in a 250-ml shake flask for 10 h with agitation of 150 rpm and temperature at 37°C: glucose 60 g/L, beef extract 10 g/L, peptone 10 g/L, yeast extract 10 g/L, and sodium chloride 5 g/L at pH 7.0 [16].

2.2. Medium composition for acetoin production

The fermentation medium used for this work was the significant optimized medium of Xiao et al. [16], which was then modified. The nutrients used comprised the following (g/L): glucose 150, K_2HP0_4 0.5 g, CH_3COONa 0.5 g, NaCl 5 g, and $MgSO_4.7H_2O$ 0.5 g, while 1 g/L of three different nitrogen sources were used in the preliminary experiment (corn steep liquor, yeast extract, and beef extract). The medium was adjusted to pH 7.0 and autoclaved at 121°C for 15 min. The flasks were incubated at 37°C with an orbital shaker at 150 rpm for 7 days.

2.3. Batch fermentation study

The preliminary experimental study of acetoin production was performed with 50 mL of glucose solution (100 g/L) measured into 250-mL Duran flask, and the growth effect of three complex nitrogen sources (yeast extract, beef extract, and corn steep liquor) were tested for acetoin fermentation nutrients. The pH of the medium was adjusted with 120 g/L of NaOH and 36.5 g/L of HCl buffer solutions. Subsequently, 5% volume fraction of inoculum size was added aseptically to the flask. The flasks were transferred into the environment-controlled incubator shaker (platform shaker, model: FSIM SP016) at 30°C and 150 rpm. Fermentation was performed for 168 h with 12-h sampling interval.

2.4. Experimental design by Box-Behnken Design

A three-level factor was employed to generate 17 experimental runs by considering the effect of glucose concentration (g/L), inoculum size (% v/v), and corn steep liquor (% w/v). The range and the levels of the independent variables investigated using the Box-Behnken experimental design (**Table 1**) were chosen based on variables previously reported to influence acetoin [11, 26]. The minimum, center point, and maximum levels of each variable were coded as −1, 0, and +1, respectively.

A second-order mathematical equation, including all interaction terms, was used to calculate the predicted response:

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} b_{ii} X_i^2 + \sum_{i<j}^{k} b_{ij} X_i X_j + e \tag{1}$$

where Y is response variable (acetoin concentration), b_0 is the intercept value, b_i (i = 1, 2…k) is the first-order model coefficient, b_{ij} is the interaction effect, and b_{ii} represents the quadratic coefficients of X_i. X_i and X_j are the input variables that influence the response variable and *e* represents the random error.

2.5. Statistical analysis

The observed data were subjected to multiple regression analysis using Design-Expert versions 10.0 (Stat Ease Inc., Minneapolis, USA) to obtain the coefficients of the quadratic equation. The *F*-value and the probability *p*-value were used to appraise the significance of the model. The coefficient of determination (R^2) and adjusted R^2 was calculated to evaluate the performance of the regression equation. The behavior of the model in the experimental area

Factor	**Unit**	**Symbols**	**Coded factors**		
			0	**−1**	**1**
Glucose	(g/L)	X_1	50	100	150
CSL	(% w/v)	X_2	5	10	15
Inoculum size	(% v/v)	X_3	2	3.5	5

Table 1. Factors and their levels for Box-Behnken design.

was investigated graphically. Statistical evaluation of the model was carried out using analysis of variance (ANOVA).

2.6. Analytical methods

2.6.1. Reducing sugar analysis

Reducing sugar concentration was analyzed using the dinitrosalicylic acid (DNS) method [27] and the results were expressed as glucose equivalent. To 1 mL of the supernatant, 3 mL of the DNS solution was added in the test tube and boiled for 15 min, cooled, and diluted appropriately after which the absorbance was measured at a wavelength of 540 nm using a UV–Visible Spectrometer (GBC Cintra 2020).

2.6.2. Biomass concentration determination

Dry cell weight (DCW) was obtained by centrifuging an aliquot of the sample followed by drying the cell pellet to a constant weight using an electric oven (Scientific, series 2000), in a pre-weighed centrifuge tube, at 105°C for approximately 24 h. It was later cooled in a desiccator. The biomass concentration was calculated on the basis of the volume of the fresh sample as the difference between the weight of the empty tube and the final weight of the tube plus the dried biomass after drying and cooling [28, 29].

2.6.3. Acetoin concentration determination

Acetoin was determined by the modified Voges-Proskauer (VP) reaction of Westerfield [30]. An aliquot of the sample solution was pipetted into a 25 cm^3 calibrated flask. A total of 2.5 cm^3 of 1-naphthol solution and 1.0 cm^3 of creatine solution were added. After adjusting the mixture to volume and shaking vigorously, the solution was kept at 30°C. The color intensity of the complex was determined by measuring the absorbance after 40 min at 530 nm using a UV–Visible Spectrometer of 2020 GBC Cintra model [31].

3. Results and discussion

3.1. Preliminary evaluation of complex nitrogen sources on AC production

The study in **Figure 2** shows that CSL supports rapid utilization of the reducing sugar (from 150 to 84 g/L) within the first 60 h of fermentation [32], the resultant acetoin and biomass growth being maximum during this period. The maximum biomass growth is found to be fairly constant at ~ 8 g/L until the 144 h when it starts to decline. Likewise, the maximum acetoin concentration is found to be ~ 7 g/L after 60 h of fermentation and then declines. The decline in the acetoin concentration could be attributed to the complete metabolism of glucose in the fermentation medium. Although the biomass concentration remained constant after the 60 h of fermentation, it can be assumed that the energy derived from reducing sugar metabolism was channeled toward cell maintenance since biomass growth remained constant and acetoin was still produced till the fermentation lapse. It has been shown previously that CSL is a rich source of proteins, amino acids, minerals, vitamins, and trace elements and can be used as nutritional supplement [32]. The addition of CSL reduced the fermentation time and promoted the growth and fermentation of the strain.

On the other hand, when yeast extract was used as the nitrogen source in the fermentation media, as depicted in **Figure 2b**, after reducing 150 g/L of sugar, the results showed a rapid consumption of the reducing sugar when compared to **Figure 2a**. More than 97% of the reducing sugar was converted (during the first 84 h of fermentation), the acetoin concentration approached a maximum, and the biomass growth was constant at 8.6 and 7.7 g/L, respectively. The wide range of amino acids, peptides, vitamins, inorganic salts, and carbon in growth media of yeast extract supports the biomass growth and rapid sugar utilization [33].

In **Figure 2c**, the extract was used in place of CSL and yeast extract as earlier discussed (**Figure 2a** and **b**). The beef extract is a mixture of peptides and amino acids, nucleotide fractions, organic acids, minerals, and some vitamins. Its function can, therefore, be described as complementing the nutritive properties of peptone by contributing minerals, phosphates, energy sources, and those essential factors missing from peptone [34]. The glucose was almost depleted after 96 h till the end of the fermentation lapse. It can be deduced from the study that the beef extract supports the utilization of glucose consumption as more than 98% of the glucose has been consumed within 96 h of fermentation.

To see the clear difference of the complex media earlier considered, the acetoin fermentation was done without the nitrogen sources (**Figure 2d**) but with the simple salts in the fermentation

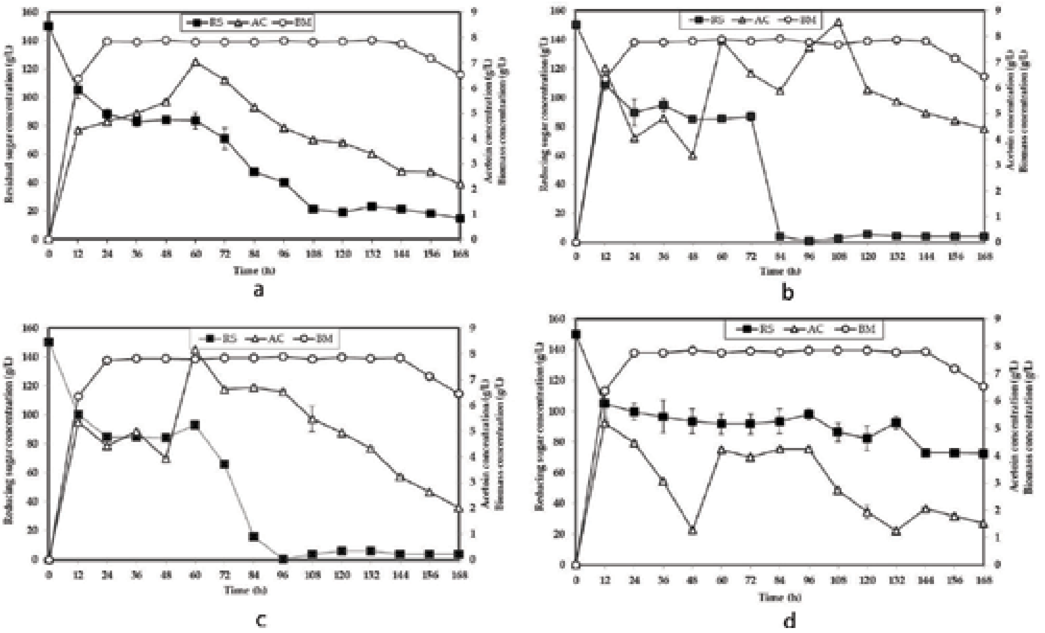

Figure 2. (a) Plots of AC fermentation using corn steep liquor as nitrogen source. (b) Plots of AC fermentation using yeast extract as nitrogen source. (c) Plots of AC fermentation using beef extract as nitrogen source. (d) Plots of AC fermentation using none of the complex media as the nitrogen source. (RS–reducing sugar; AC–acetoin; BM–biomass).

media. A maximum acetoin of about 5.2 g/L was obtained during the first 12 h of the fermentation, after which there was no significant change in the biomass growth from that period until the lapse time of fermentation. About 50% (72.53 g/L) of sugar concentration was not consumed until the fermentation time lapse of 168 h, and the sluggish consumption of glucose could be traceable to the lack of rich nitrogen sources, which was needed as a nutritional supplement [28].

3.2. Metabolism of corn steep liquor on AC production

It was observed in the preliminary evaluation of nitrogen sources discussed earlier (**Figure 2a–d**) that corn steep liquor produces acetoin at a short time interval when compared to other nitrogen sources. Therefore, the fermentation time interval of acetoin was reduced from the initial 168 h (**Figure 2a–d**) to 48 h (**Figure 3**) and sample taken at every 2-h interval, to investigate the biomass growth, utilization of glucose, and the acetoin accumulation when corn steep liquor was used as nitrogen source. The results show that the accumulated acetoin and the biomass growth were already at the peak of 7.03 and 7.83 g/L, respectively, in the first 36 h of fermentation (**Figure 3**). The rapid utilization of reducing sugar (from 150 to 66 g/L) within 36 h of fermentation was due to high amino acids and polypeptides, which are excellent sources of nitrogen in corn steep liquor and has been reported to support the growth of most microorganism [35]. CSL comprises a mixture of reducing sugars that contribute to the nutritional growth of the bacteria with a steady increase in biomass growth (7.7–7.8 g/L) from 18 to 46 h when it starts to decline [36]. It can be affirmed from the findings that corn steep liquor hastens fermentation of acetoin at short time interval and this makes large-scale production of acetoin cost-effective.

3.3. Optimization of AC production using response surface method

After the preliminary studies, RSM coupled with Box-Behnken design (BBD) was used for the optimization of the fermentation process with respect to glucose concentration, CSL

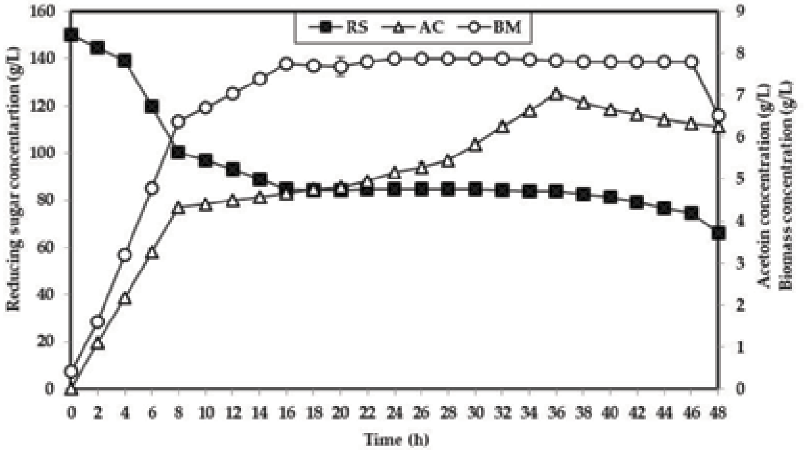

Figure 3. Acetoin growth profile using corn steep liquor at short fermentation time interval. RS–reducing sugar; AC–acetoin; BM–biomass.

concentration, and inoculum size with a view to maximize the AC production. **Table 2** shows the experimental conditions investigated together with the observed and predicted values. The data were fitted using the following second-order mathematical equation:

$$\begin{aligned} Y = {} & 7.81 - 1.37\,X_1 + 2.56\,X_2 - 0.61\,X_3 - 0.17\,X_1X_2 - 0.57\,X_1X_3 - 1.02\,X_2X_3 \\ & - 1.25\,X_1^2 - 0.50\,X_2^2 - 1.09\,X_3^2 \end{aligned} \qquad (2)$$

where Y is the acetoin (AC) produced in g/L and X_1 is glucose concentration, X_2 is corn steep liquor, X_3 is Inoculum size. The residuals between the observed and predicted (**Table 2**) values in this work revealed good fit of the equation as shown by the parity graph which is a measure of agreement between the observed and predicted values (**Figure 4**). These observations implied that the model developed for the fermentation process adequately described the actual relationship among the selected factors.

The three-dimensional graph and contour plot, which is depicted in **Figure 5(a)** and **(b)** shows the relationship between corn steep liquor and glucose concentration when acetoin production is at the maximum (10.70 g/L). Also, the *p*-values of the model terms were significant at $p < 0.05$ (**Table 3**). Also, the observed low *p*-value of 0.0001 together with the corresponding *F*-value of 11.09 showed that the model obtained was significant. The *F*-value and *p*-value do not differentiate between negative and positive significant effects of each term in the model [37]. **Table 3** displays the test of significance and ANOVA of the regression equation results. The coefficient of determination (R^2) is used to assess the goodness of fit of the regression

Run	X_1 (g/L)	X_2 (% w/v)	X_3 (%v/v)	Observed AC (g/L)	Predicted AC (g/L)	Residuals
1	100 (0)	10 (0)	3.5 (0)	7.68	7.81	−0.13
2	150 (1)	10 (0)	2 (−1)	4.32	5.28	−0.96
3	150 (1)	5 (−1)	3.5 (0)	2.47	2.29	0.18
4	100 (0)	10 (0)	3.5 (0)	7.68	7.81	−0.13
5	100 (0)	5 (−1)	2 (−1)	3.66	3.24	0.42
6	100 (0)	15 (1)	2 (−1)	10.69	10.41	0.28
7	50 (−1)	10 (0)	2 (−1)	7.14	6.88	0.26
8	100 (0)	15 (1)	5 (1)	6.49	7.15	−0.66
9	50 (−1)	10 (0)	5 (1)	8.00	6.8	1.20
10	150 (1)	10 (0)	5 (1)	2.91	2.92	−0.01
11	100 (0)	10 (0)	3.5 (0)	7.68	7.81	−0.13
12	100 (0)	5 (−1)	5 (−1)	3.53	4.06	−0.53
13	150 (1)	15 (1)	3.5 (0)	7.88	7.08	0.80
14	50 (−1)	15 (1)	3.5 (0)	9.74	10.16	−0.42
15	100 (0)	10 (0)	3.5 (0)	7.70	7.80	−0.11
16	100 (0)	5 (−1)	3.5 (0)	5.72	4.74	0.98
17	50 (−1)	5 (−1)	3.5 (0)	3.65	4.69	−1.04

Table 2. BBD of three independent factors for AC production including the coded levels of each parameter.

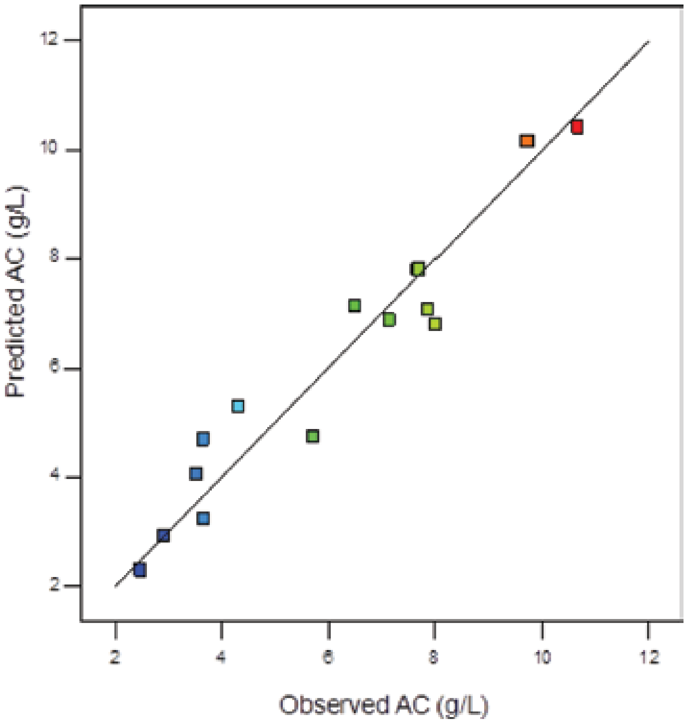

Figure 4. Parity plot of acetoin production.

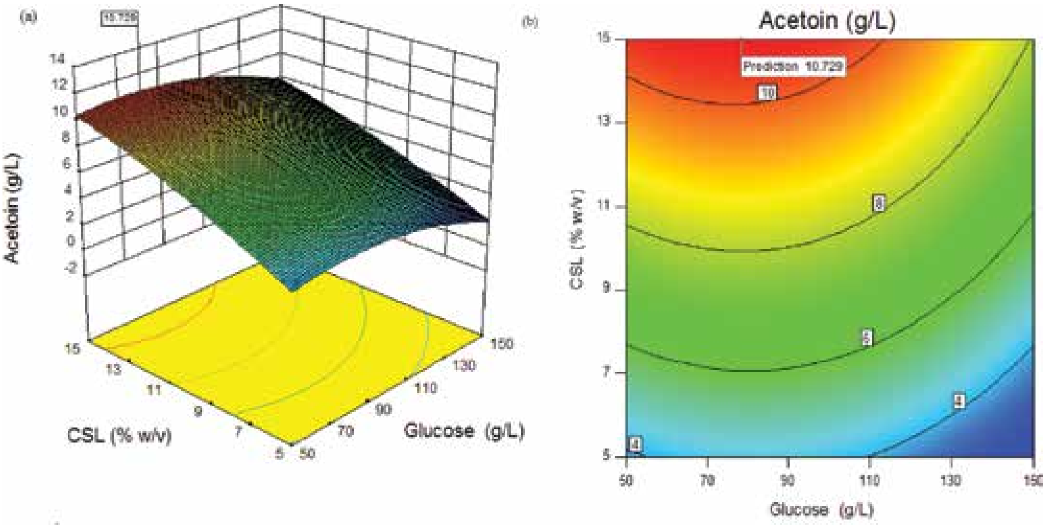

Figure 5. Contour and response surface plots. (a) The response surface plot and (b) contour plot showing the effects of corn steep liquor and glucose on acetoin production.

equation. R^2 of 0.930 of the model demonstrated a good correlation between the observed and predicted values. It showed that 93% sample variation for AC produced is attributable to the independent factors and just 0.70% of the total variations is not described by the model

Factor	Sum of squares	df	Mean square	*F*-value	*p*-value
X_1 (Glucose)	14.99	1	14.99	16.51	0.0048
X_1^2	6.52	1	6.52	7.18	0.0315
X_2 (CSL)	57.85	1	57.85	63.73	0.0001
X_2^2	1.06	1	1.06	1.17	0.3160
X_3 (Inoculum size)	2.98	1	2.98	3.28	0.1131
X_3^2	4.98	1	4.98	5.48	0.0517
X_1X_2	0.12	1	0.12	0.13	0.7317
X_1X_3	1.29	1	1.29	1.42	0.2724
X_2X_3	4.14	1	4.14	4.56	0.0701
ANOVA					
Model	90.63	9	10.07	11.09	0.0022
Error	3.000E-004	3	1.000E-004		
Total sum of squares	96.99	16			
$R^2 = 0.93$, Adjusted $R^2 = 0.90$					

Table 3. Test of significance for every regression coefficient and ANOVA.

[28, 38]. The adjusted R^2 of 0.90 proved that the model was significant. It has been suggested that R^2 should be less or equal to 80% for the good fit of a model [39].

3.4. Model validation

The optimum values of the three factors selected for the fermentation process were obtained by solving Eq. (2) using the Design-Expert software package (version 10.0). The optimal condition was statistically predicted as glucose concentration of 78.40 g/L, CSL of 15.00% w/v, and inoculum size of 2.70% v/v. Under this condition, the AC concentration predicted was 10.73 g/L. In order to validate the model, the optimal condition values were applied to three independent experimental replicates and the average value of AC produced was 10.70 ± 0.1 g/L. The correlations between predicted and experimental values after optimization infer the validity of the response model and the existence of an optimum point [40]. The bar chart (**Figure 6**) is a graphical view for each optimal solution showing the desirability of every dependent and independent factor with combined value. Independent factors are shown with red bars, while the dependent response and combined values are displayed in blue. The desirability result is accurate as it falls within the acceptable value ranging between 0.8 and 1 [41]. In **Table 4**, variance inflation factor (VIF) obtained showed that the center points are orthogonal to all other factors in the model. The 95% confidence interval (CI) bounds showing high and low help to hypothesize that there is 95% probability of including the right predicted responses by the model, and there is only 5% chance that the observed value lies either below or above the level of confidence limits. The coefficient estimate shows the confidence interval

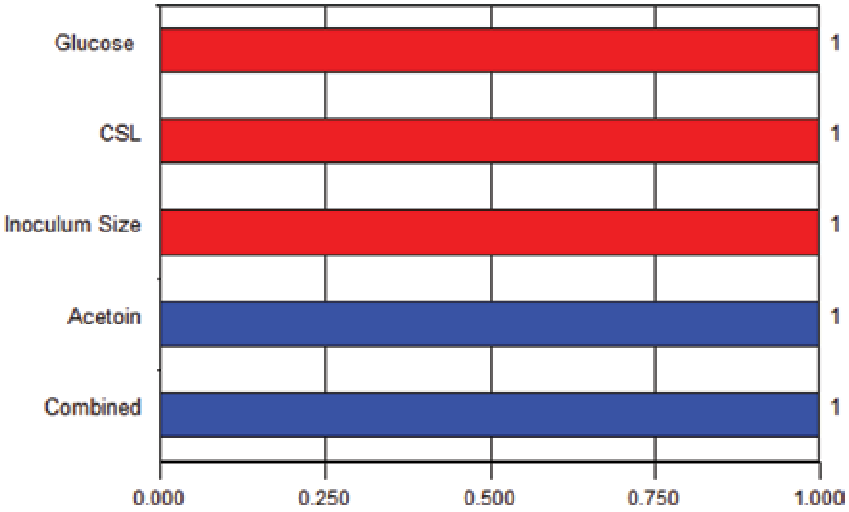

Figure 6. Numerical optimization bar graph of AC production.

Factor	Coefficient estimate	df	Standard error	95% CI low	95% CI high	VIF
Intercept	7.81	1	0.47	6.71	8.91	
X_1 (Glucose)	−1.37	1	0.34	−2.17	−0.57	1.00
X_2 (Corn steep liquor)	2.56	1	0.32	1.80	3.32	1.02
X_3 (Inoculum size)	−0.61	1	0.34	−1.41	0.19	1.00
X_1X_2	−0.17	1	0.48	−1.30	0.96	1.00
X_1X_3	−0.57	1	0.48	−1.69	0.56	1.00
X_2X_3	−1.02	1	0.48	−2.14	0.11	1.00
X_1^2	−1.25	1	0.47	−2.35	−0.15	1.01
X_2^2	−0.50	1	0.47	−1.60	0.60	1.01
X_3^2	−1.09	1	0.47	−2.19	0.011	1.01

df: degree of freedom; VIF: variance inflation factor; CI: confidence interval.

Table 4. Regression coefficients and significance of response surface quadratic.

around the model coefficient and the standard error less than 1 shows the statistical accuracy of the predicted responses (**Table 4**).

4. Conclusion

The feasibility of corn steep liquor to replace yeast extract and beef extract, which is an expensive nutrient source in acetoin fermentation, was investigated. Corn steep liquor—a low-cost nitrogen source—competes with other complex nutrients (yeast extract and beef extract) for acetoin production and statistical optimization was carried out in batch fermentation. The model that best described the AC fermentation process was a quadratic model with R^2 of 0.930. The most significant positive factor for the process was glucose concentration and corn steep liquor, while inoculum size was an insignificant factor in the AC fermentation. Optimal condition predicted for the three independent factors were a glucose concentration of 78.40 g/L, CSL of 15% w/v, and inoculum size of 2.70% v/v, which were validated experimentally with AC concentration of 10.70 ± 0.1 g/L. Based on study results, it can be concluded that the optimization methodologies developed were effective in ascertaining the amount of CSL required for commercial acetoin production, and it reduced the cost, time, and effort associated with experimental techniques.

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Conflict of interest

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; and in the decision to publish the results.

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Chapter 7

Energy Prospects of Hazardous Sludge from Wastewater Treatment Facilities

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Additional information is available at the end of the chapter

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Abstract

Reduced reserves of fossil fuels, global warming issue, population growth rates and consumptive lifestyles trigger awareness of the need to utilize alternative energy sources as a substitute for the use of fossil fuels. The carbon compounds contained in wastewater sludge is one of the materials that has the potential to be an alternative energy source if managed with proper method. In relation to this, the main objective of this research is to identify the prospect of several technologies to treat organic sludge in terms of mass reduction and energy recovery as a basis for feasibility study and further development. Simulations carried out on wastewater sludge from Jababeka's centralized wastewater treatment facilities showed that thermochemical processing methods were quite effective in reducing sludge mass. Reduction of mass occurs due to the decomposition of carbon compounds resulting in changes in the size of sludge particles. In addition, green energy produced can also be used to fulfill some needs in treatment facilities and can be a substitute for the use of fossil fuels. Overall, based on the results of the feasibility study simulation, it can be concluded that the thermochemical processing method can be further considered to develop into the pilot scale.

Keywords: hazardous sludge, energy recovery, renewable energy, sewage, wastewater treatment

1. Introduction

The need for energy source is one of the important things in human life. Fossil fuel, geothermal, water potential, and nuclear energy are some energy sources that have been commonly used. In addition to some of these energy sources, wind energy, solar radiation, ocean waves, biomass, and other renewable energy sources have also been widely researched and developed as an alternative energy source. Nevertheless, until now fossil fuels are still one of the primary energy sources that cannot yet be completely replaced by other types of energy sources. The decrease in availability of fossil fuels as non-renewable energy sources is inversely proportional to the increasing population of the world. Raising awareness of the limited reserves of fossil fuel and of the need for another energy source as alternative energy source is needed. One alternative energy source that can be considered is the biomass content of sludge produced from biological wastewater treatment. Carbon compounds contained in biological sludge (bio-sludge) can be converted into energy through thermal process, biodigestion, lipid/oil extraction, or other methods that are in accordance with its characteristics [1, 2, 12, 15, 25, 34]. Therefore, the main objective of this research is to identify the prospect of several technologies to treat organic sludge in terms of mass reduction and energy recovery as a basis for feasibility study and further development. The thermal process of converting biomass to energy is also accompanied by a decomposition process of complex carbon into a simpler form of carbon compounds. So that, in this case, not only the conversion of biomass into energy, but also the mass reduction of sludge should be processed and managed to minimize the negative impacts that can be generated from the sludge generated by the wastewater treatment process [11].

Before discussing further the next section, it is necessary to clarify in advance some terms in this paper. What is meant by sewage is liquid waste (in this case, it is wastewater) that flows in the sewer [31]; so, the terms sewage and wastewater will be used interchangeably according to the context of the sentence. Sewage sludge is mud that originated from a sewer, whereas treated sewage sludge means sludge that is produced from the treatment process in wastewater treatment facilities.

2. Hazardous sludge: properties and its potency

The list of hazardous waste from non-specific sources found in Annex 1 of the Republic of Indonesia government regulation No. 101/2014 concerning the management of hazardous and toxic waste stated that sludge produced from integrated wastewater treatment facilities in industrial estate was classified as hazardous waste category 2 [10]. In this category, the waste in question is declared as toxic waste which is harmful to the environment and living things.

2.1. The origin of sludge: case study of Jababeka's wastewater treatment facilities

In a centralized wastewater treatment facility, especially in an industrial estate, wastewater from each factory located within the industrial area will be drained through sewerage. Wastewater generated from the production process should be treated in advance so that it is in accordance with the wastewater quality standards determined by the industrial estate manager. In addition to its characteristics, the volume of wastewater discharge through the sewer should also follow the regulations determined by the industrial estate manager. It is required to ensure that the wastewater that flows to the treatment facility has characteristics that are in accordance with the processing capability and capacity of the existing treatment facilities. The treatment process is generally divided into several stages, among others primary treatment, secondary treatment, tertiary treatment, and other treatment options according to the wastewater characteristics to be treated.

Referring to the regulation of Republic Indonesia environment minister No. 5 year 2014 concerning wastewater quality standards, stated that each type of industry that produces wastewater from the results of its activities and conducts types of treatment activities, it is a mandatory to comply with the applicable quality standards [23]. Likewise, with centralized wastewater treatment facilities located in industrial estates, it is mandatory to comply with the applicable quality standards. One of the centralized wastewater treatment facilities in the industrial estate in Indonesia is the Jababeka's wastewater treatment facility located in Bekasi Regency, West Java. The main process in this treatment facility is a biological treatment process equipped with other treatment process units.

As can be seen in **Figure 1**, there are several treatment stages at the Jababeka's wastewater treatment facilities. Among them are the removal stages of sand, gravel, and rough mud on the grit chamber unit. Furthermore, wastewater will flow due to gravity toward the primary settling tank unit. In this unit, suspended solids will settle, while floating material will be separated with the scum collector and then flow to the sludge treatment unit. The primary settling tank effluent is flowed to the oxidation ditch which utilizes biological process (activated sludge) to decompose pollutants contained in wastewater. This process will produce

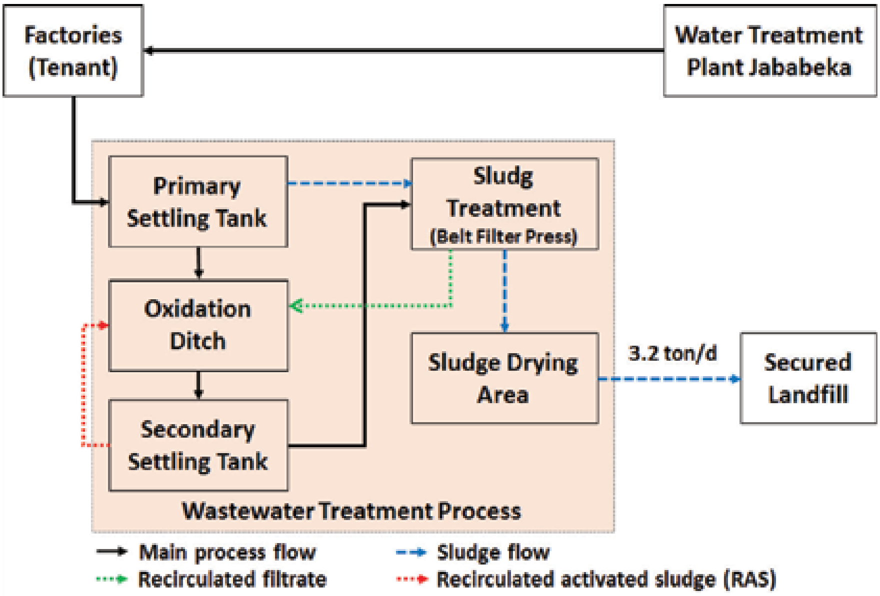

Figure 1. Schematic flow diagram of Jababeka's wastewater treatment facilities.

biological floc which is then deposited in the secondary settling tank unit. A part of the sludge produced in this process is recirculated to maintain the continuity of the process, while other parts are channeled to the sludge treatment unit.

Referring to the process description, it can be identified that there are two types of sludge produced from this treatment facility. Sludge produced from primary settling process mainly is inorganic material (about 55–65%) that comes from heavy suspended solid settled by physical gravity process. The total sludge production from primary treatment was about 500 kg/day for a flow rate of 13,300 m^3/day of wastewater.

The second type of sludge is produced by secondary settling process that mainly contains 60–70% of organic material from organic floc formed in the aeration tank. The quantity of organic sludge is much bigger than inorganic sludge due its relation with biological process control. The management of activated sludge concentration in aeration tank and sludge concentration in recirculation flow by distribution box unit is very significant for maintaining wastewater treatment process properly. In this case, the production of large amounts of organic sludge cannot be avoided. The organic sludge production is about 3200 kg/day (55% dry solid) for a flow rate of 13,300 m^3/day of wastewater with its calorie about 2000–2500 kcal/kg of 100% dry sludge. This quantity contributes a very significant amount in the wastewater treatment operational cost. Reducing quantity or converting the organic sludge to the alternative materials or energy is very helpful in terms of reducing operational cost.

2.2. Sewage sludge and treated sewage sludge properties

Previously, research has been carried out by several researchers regarding the analysis of the characteristics of sludge collected from sewer, as well as sludge generated from wastewater treatment process in wastewater treatment facilities. There are two major groups of sludge types whose characteristics are analyzed, which are municipal and industrial sludge. Municipal sludge is sludge originating from domestic activities in connection with activities in a residential area, while industrial sludge is produced from production processes in various fields of industry.

Most of the previous research studies summarized in **Table 1** are regarding characteristics of sludge from urban/municipal activities [2, 7, 8]. Several reports concerning industrial sludge treatment have also been summarized [4, 5, 19]. Not all of the research studies summarized in **Table 1** are using treated sludge as the feedstock for energy recovery process. Some researchers use organic sludge which is the by-product of the manufacturing process of TFT-LCD and sludge from pulp and textile industries [4]. In addition, there is a review report of various sludge characteristics of each wastewater treatment stage [20].

When compared carefully based on the summary from **Table 1**, it can be observed that organic sludge which has the highest amount of volatile matter is sludge originating from a centralized biological wastewater treatment process. It can be observed that the volatile matter content in the sludge analyzed is in the range of 47.00–77.00%. If it is assumed that the main component of volatile matter is carbon compounds, which in the process will be converted into

The origin of sludge (feedstock)	C	H	O	N	S	Volatile matter	Fix carbon	Ash
	%	%	%	%	%	%	%	%
Dry treated sewage sludge, digested (municipal) [2]	29.50	4.67	20.20	5.27	1.31	—	—	39.04
Recycling of organic sludge from TFT-LCD manufacturing process [4]	50.00	—	—	9.00	2.10	—	—	—
Pretreated pulp industrial sludge [5]	18.48	1.78	78.82	0.83	—			
Pretreated textile industrial sludge [5]	32.15	5.73	59.04	1.36	1.64			
Dry treated sludge from urban wastewater treatment [7]	38.82	6.19	—	5.78	1.17	64.90	7.90	27.20
Dry treated sludge from urban wastewater treatment [8]	28.50	4.30	22.40	4.10	0.80	47.00	6.40	39.90
Dried sewage sludge [9]	36.45	5.93	25.74	7.03	0.77	59.06	9.36	24.08
Urban sewage plant [18]	36.11	5.25	—	6.50	1.03	57.22	6.09	31.27
Dried sludge from wastewater treatment plant of thermal power plants [19]	32.30	4.90	24.90	5.30	0.57	64.70	—	—
Primary treatment [20]	51.50	7.00	35.50	4.50	1.50	65.00	—	—
Biological treatment (low) [20]	52.50	6.00	33.00	7.50	1.00	67.00	—	—
Biological treatment (low and mid) [20]	53.00	6.70	33.00	6.30	1.00	77.00	—	—
Primary and biological (mix) [20]	51.00	7.40	33.00	7.10	1.50	72.00		
Digested [20]	49.00	7.70	35.00	6.20	2.10	50.00		

Table 1. Characteristics of sludge from previous research.

flammable gas and/or flammable oil, it means that volatile matter can be expressed as volatile carbon and can be used as a benchmark in determining the energy content. Furthermore, it can be expressed to determine the calorific value of the flammable gas and/or flammable oil produced from thermal conversion process. In fact, volatile matter contains not only carbon compounds but also volatile components such as nitrogen compounds, sulfur, and other components varying in number depending on the process characteristics and complex compounds involved. It shows that gas produced from the thermal conversion still requires a purification process to minimize the negative impact of emission from combustion (**Figure 2**).

2.3. Conversion method of sludge to energy

Before going further, it is necessary to clarify the terms that will be discussed in this section. What is meant by conversion of sludge to energy, in this context, can be the decomposition process of carbonaceous (organic) sludge into gas/fuel oil which will then be used as an

Figure 2. Treated industrial sludge in Jababeka's wastewater treatment facility. (Source: Kurniawan et al.).

energy source, or it can be in the form of direct conversion of sludge to energy in the form of heat released from combustion.

Organic sludge has the potential to be an alternative sustainable energy source if managed with the proper and efficient method. What needs to be realized is, to convert sludge into an energy source, a certain amount of energy is needed in the conversion process. In **Table 2**, we can observe several methods of converting feedstock into energy sources through various types of process. The sludge to energy conversion discussed in this paper covers the physical, biochemical, thermochemical, and transesterification conversion methods.

2.3.1. Physical conversion method

What is discussed in this section is the method of compacting sludge into a form of pellets or briquettes for later use as solid fuel known as refuse-derived fuel (RDF). It is done to facilitate storage and transport compared to the original form. The compacting process will directly affect the water content. In the direct combustion process, the low water content will increase the ease of solids to burn. It will affect the combustion temperature and heat value generated from combustion, because the heat produced is only used for the oxidation of organic matter rather than vaporizing the water content. Besides being burned directly, RDF sludge can also be applied to the pyrolysis process or gasification to produce synthesis gas or pyrolysis oil (**Figure 3**).

Conversion method	Feedstock	Main process
Anaerobic digestion	Wastewater sludge from food-processing industry [32].	Fermentation using a clostridium strain to produce hydrogen and methane.
Pelletization	Recycling of organic sludge from TFT-LCD manufacturing process [4].	Characterization of sludge refuse-derived fuel (RDF) and its combustion behavior and properties
Pelletization	Urban wastewater sludge from biological treatment [13].	Combustion characteristics of pure biomass RDF and RDF from sludge-biomass mixture. Comparative study of the energy consumption for pelletization process.
Pyrolysis	Treated wastewater sludge originating from domestic, commercial and industrial activities [13].	Characterization of fundamental properties of the wastewater sludge pyrolysis product in a fixed bed pyrolysis reactor.
Pyrolysis	Wastewater sludge from petrochemical industry; oily sludge from primary decanter [14]	Pyrolysis product characterization of wastewater sludge in a fixed bed pyrolysis reactor.
Pyrolysis	Wastewater biosolids [21].	Pyrolysis product characterization of wastewater biosolid in a fixed bed pyrolysis reactor and its energy comparison for required and resulting energy content.
Pyrolysis	Combination of rice waste and treated sewage sludge [30]	To produce bio-oil in fluidized-bed reactor through fast pyrolysis.
Pyrolysis	Thickened excess activated sludge, dewatered digested sludge, and dried excessive activated sludge [27].	Flash pyrolysis to produce pyrolysis oil in fixed bed reactor.
Gasification	Solar dried-treated wastewater sludge [29].	Syngas production in semi-batch steam gasification reactor.
Gasification	Undigested and dried-treated sewage sludge pellets [22].	Gasification of feedstock pellets in fixed bed downdraft reactor.
Transesterification	Wet activated sludge [17].	Hexane-lipid extraction and non-catalytic biodiesel production in tubular glass transesterification reactor.
Transesterification	Dried sludge of food processing plant [15].	In situ transesterification of sludge in subcritical mixture of methanol and acetic acid.

Table 2. Various conversion methods of sludge to energy source.

2.3.2. Biochemical conversion method

The decomposition of organic compounds using biological processes is one method that can be done to produce alternative energy sources. Biogas which has the main content of methane gas is produced from the decomposition process under controlled anaerobic conditions. Several stages in the biogas production process include the stages of hydrolysis, liquefaction, and fermentation; the formation of hydrogen and acetic acid; and the last is the methane gas formation stage [25]. Each stage of the process that the sludge goes through will involve different types of enzymes produced from the metabolism of anaerobic bacteria. Previous research has reported on critical review along with the biogas production process from wastewater sludge [25].

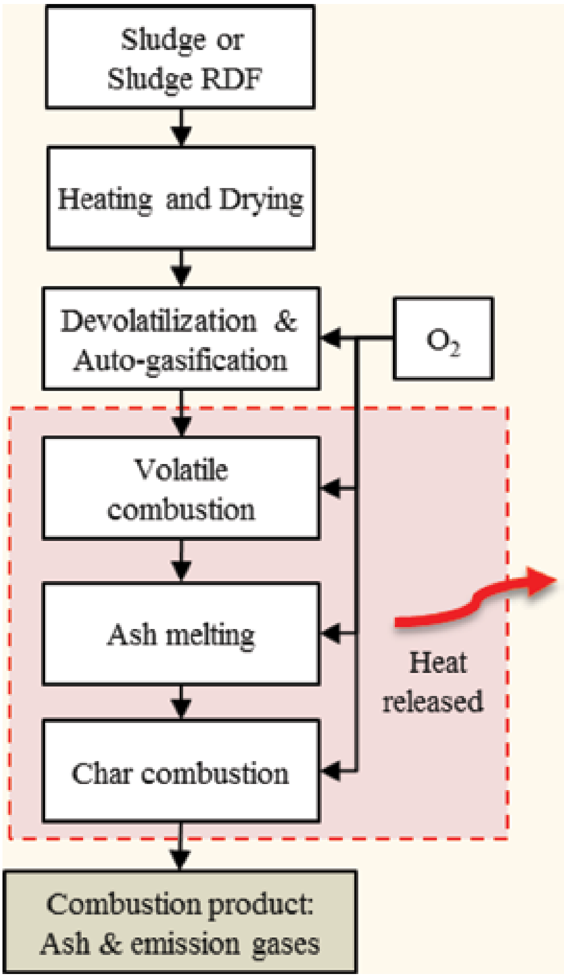

Figure 3. Pathway of sludge combustion process (Source: Kurniawan et al.).

2.3.3. Thermochemical method

In the thermochemical method, combustion process is one part that cannot be separated. Heat is produced from chemical reactions that occur due to the decomposition of organic compounds through oxidation process. Some types of treatments classified as thermochemical methods include direct combustion, incineration, pyrolysis, and gasification. The combustion process takes place in a compartment, which is usually known as combustion chamber. In this compartment, several types of configuration are known based on the type of working fluid flow pattern (updraft and downdraft) and the type of solid bed (fixed and fluidized bed) (**Figure 4**).

In the fixed bed type, solid bed is on the screen or perforated plate in fixed position. As for the type of fluidized bed, solids are suspended in the working fluid flow. Updraft and downdraft flow show the pattern of working fluid in the bed reactor. Combination of solid bed types and the types of working fluid flow pattern can be applied to pyrolysis and gasification reactor according to needs.

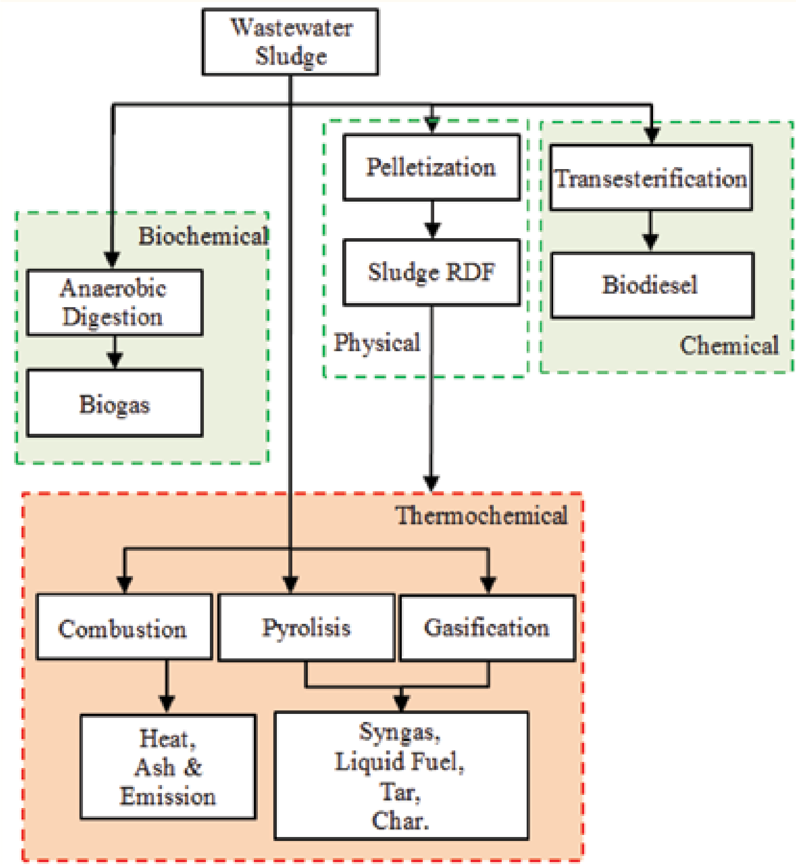

Figure 4. Sludge-energy conversion pathway (Source: Kurniawan et al. with modification).

The most fundamental difference between direct combustion with pyrolysis/gasification is the amount of oxygen used in the oxidation process. A certain amount of oxygen with sufficient stoichiometric concentration (even in excessive condition usually) is required in direct combustion, so that carbonaceous compound will be completely oxidized to carbon dioxide and water vapor. An imbalance in the amount of stoichiometric oxygen will result in incomplete combustion, indicated by the production of volatile compounds other than carbon dioxide. This phenomenon occurs in the gasification process, the supply of oxygen to the combustion chamber is intentionally limited in such a way that it does not meet the stoichiometric equilibrium as occurs in the complete combustion of carbonaceous compounds. In this process, flammable synthesis gas will be produced. In the context of the shortness of the duration and stages of the mass reduction process, and the flexibility of renewable energy that can be produced, gasification is a viable option compared to direct combustion or anaerobic digestion method .

Typical oxidation medium in combustion is air, whereas in gasification, it can be air, pure-oxygen, steam, or other substances [29]. In gasification, the energy released from decomposed solid fuel is packed into chemical energy in the form of gas fuel . On the contrary, combustion decomposes solid fuel and releases as much as possible the energy content in the form of heat. There are four stages of gasification process, heating and drying, devolatilization, gas-gas reaction, and char gas reaction [3]. At the drying stage, there is an increase in temperature of carbonaceous sludge which results in evaporation of sludge-water content. At the devolatilization stage, thermal cracking process occurs that produces light gas products such as H_2, CO, CO_2, CH_4, H_2O, and NH_3. This devolatilization stage is also known as pyrolysis stage. In the gasification process, a gasification medium is required in the form of air, oxygen, or steam. In contrast to pyrolysis, no medium is required, but heat is required as a driving force to release the volatile compounds. Based on the explanation, it can be said that gasification is a pyrolysis process that is optimized to convert solid fuel into synthesis gas. The next two stages are the chemical reaction stage between gas-gas and char-gas which will eventually produce synthesis gas (syngas).

Gasification process for pellets made from sewage sludge (sludge RDF) has been carried out by several previous researchers [22, 26, 28]. Research shows that the use of fixed bed and fluidized bed gasifiers is quite promising. The results of this study were obtained from several types of sludge which have different characteristics, so they cannot be compared with each other. The total heating value generated in the use of a fixed bed-type gasifier is around 4 MJ/m^3 with hydrogen concentration around 10–11% v/v [22]. Other studies on uncompressed sewage sludge gasification showed that the higher the oxygen content and the temperature of compressed air, the higher heating value produced [6, 33]. In addition, it can be observed that the higher the sludge humidity, the higher the hydrogen concentration and its heating value [33]. This phenomenon occurs because the water content in the form of moisture on the sludge evaporates into steam which involves a water-gas shift reaction, in this case, the equilibrium of the reaction shifts to the right due to excess concentration of carbon components and water molecule in the form of steam on the side of reactant. This is in line with the previous research which shows that high-quality syngas can be obtained from steam-gasification of wet sludge which results in higher hydrogen-carbon ratio than air-gasification or oxygen-gasification [24]. Other studies on the type of gasification using water in supercritical conditions indicate that the higher and the longer detention time will increase the yield of hydrogen and methane [1].

2.3.4. Transesterification

In addition to anaerobic digestion, direct combustion, pyrolysis, and gasification, another option for organic sludge energy recovery is the transesterification process. It involves the reaction between triglycerides and methanol under controlled conditions, either with or without the presence of a catalyst. The use of homogeneous catalyst is relatively cheap compared to the use of heterogeneous catalysts. However, homogeneous catalysts are very sensitive to free fatty acids and the water content in oil, and can trigger saponification and hydrolysis reactions [17]. The first stage of the process is to extract the oil contained in the sludge that will be reacted with methanol to produce crude biodiesel; then the refining process is carried out by separating the biodiesel fraction from the glycerin layer. Several studies on sludge energy recovery through transesterification process have been carried out in lab-scale experiments or only in the form of simulation or process review. Research about transesterification on lab scale has been carried out in a quart-tubing tubular reactor equipped with gas sensors, heaters, and other equipment to produce controlled process conditions [17]. The products resulting from esterification reaction in the form of biodiesel, which is still mixed with glycerin, are then allowed to settle for 2 hours to be separated and then analyzed by gas chromatography. Another research has analyzed challenges in terms of process commercialization, including sludge collection, optimization of biodiesel production process, maintaining quality of product, formation of soap as a by-product and its purification method, proper design of bioreactor, pharmaceutical chemical in sludge, regulatory concerns, and economics of biodiesel production [15].

2.4. Pyrolysis of treated wastewater sludge from Jababeka's treatment facility

This section is an extended article from a paper entitled "The prospect of hazardous sludge reduction trough gasification process," which was presented in scientific forum. The study of the topic originated from consideration of disposal cost of biological sludge to secure landfill. The energy produced is a by-product of the process of reducing the organic sludge mass which, if optimized, can also be an alternative energy source and it is hoped that more or less can be utilized as a substitute for fossil fuels in the area of treatment facilities.

2.4.1. General considerations

From several options of sludge to energy conversion method discussed in the previous section (see part 2.3), it can be observed that conversion technology is not a major problem, considering that up to now there are quite a number of conversion method options that have been developed. However, in the context of its implementation, it is necessary to consider several aspects including technical, economic, environmental, and other aspects that are interrelated with this.

Technically, the selection of the conversion method should conform to the characteristics of the sludge. In sludge with high oil/fat content, the extraction options for oil/fat content followed by transesterification (extraction-transesterification) are possible. The oil extracted from sludge still has carbonaceous solid, which can be treated by thermal or biochemical processing methods, whereas for sludge with low oil/fat content, the extraction-transesterification method is certainly not the proper option considering the yield will also be very low.

Another technical aspect that needs to be considered is the ease of operation. The complexity of the technology used will directly affect operational ease and will also affect the operational and energy costs. Environmental impacts that may result from the advanced treatment of sludge carried out also need to be considered. In the thermal conversion method that involves the combustion process, it must be ensured that the resulting flue gas is treated first before being released into the atmosphere. Improper treatment of flue gas can be a source of pollutants for the earth's atmosphere and may even be a contributor of gaseous pollutants, which in large quantities can exacerbate the greenhouse effect. In addition, reviews of economic aspects are also an aspect that needs to be considered, including investment cost, operational cost, energy cost, and other costs that are related to this process.

2.4.2. Simulation based on experimental data

Experiments of the pyrolysis process are carried out on a laboratory scale using pyrolysis reactor in the form of a closed stainless steel vessel equipped with a gas-fired heating system. The reactor is also equipped with a gas-liquid separator made of polypropylene and several valves to regulate the fluid flow involved in the process, as illustrated in **Figure 5**.

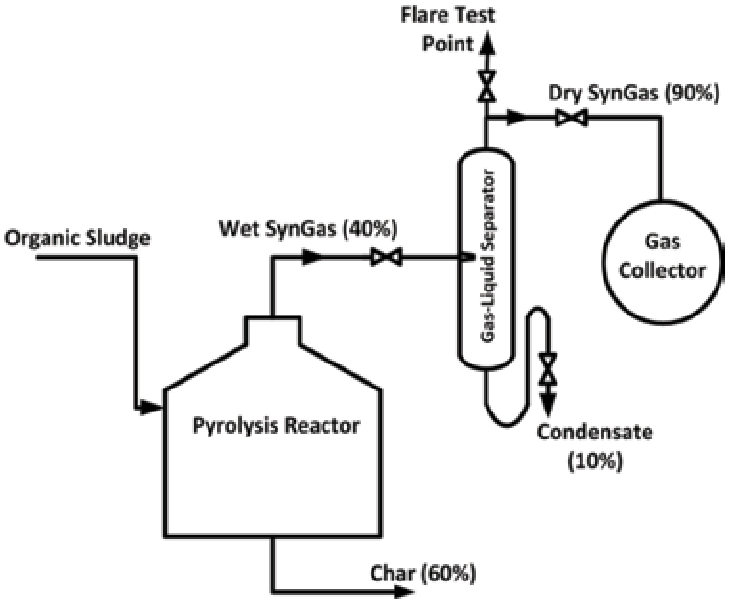

Figure 5. Simplified schematic diagram of organic sludge pyrolysis process.

Treated wastewater sludge which contain 66% of carbonaceous compound has the potential that can be used as an alternative energy source if it is managed by the appropriate method. The amount of water contained in the wet sludge (43% of the total wet basis) is removed through the belt filter press unit and then dried with sunlight in the sludge drying area, until the water content is around 10% (dry basis).

In addition to organic matter and water, there are also contents of sulfur and other minerals which amount to 4% of the dry weight.

Sludge which has reduced in its water content by about 10% is then put into a fixed-bed pyrolysis reactor so that the mass of solids is reduced by 40%. Mass loss occurs due to the decomposition process of organic matter into simpler matter. The measurement results show that the decomposition process occurs at reactor temperature up to 550°C. The fraction that is converted to gas will then flow to the gas-liquid separator which is equipped with a carbon filter layer to reduce the amount of gas impurities carried to the gas collector.

Not all gas produced from thermal decomposition process flows into the gas collector, the heavier fraction will condense in the separator because of the difference in temperature and pressure inside the reactor with those on the inside of the separator.

Differences in temperature and pressure occur due to decomposition of some solid sludge into gas accumulated in pyrolysis reactor. The wet gas fraction as a top product from pyrolysis reactor will be flow to the gas-liquid separator that allows the decrease in gas velocity so that the separation process of the gas fraction and heavier fractions can be occur. The top-most product of pyrolysis reactor that enters the separator will be separated into 90% dry gas and

10% condensate (see **Figure 5**). Another parameter analyzed is the particle size of the sludge that is treated. The initial treatment carried out in laboratory experiments is the drying process with an oven, and then reducing the lump of sludge into particle which has an average size of 11 mm. Sludge, which has been reduced in solid size, is then processed thermally so that it produces char, the remaining solid sludge that does not decompose and remains in a solid form with an average size of 4 mm (see **Figure 6**). The results of these observations indicate that the heat treatment given results in decrease in sludge particle size by about 36%, this is directly proportional to the decrease in sludge mass up to around 40%. The decrease in sludge mass and the decrease in sludge particle size indicate that decomposition of the sludge component has occurred. Components classified as volatile heat-sensitive matter are evaporated, while fixed carbon and other unevaporated components remain in the solid form (**Table 3**).

As mentioned in the previous paragraph, the decomposition process of solid sludge is indicated by a decrease in sludge particle size. And the decrease in sludge particle size also affects the total mass of sludge. The cost of managing treated wastewater sludge comes from the energy cost used to reduce the water content, in this case using a belt filter press unit. Besides that, there are sludge disposal costs involving third parties who have permits. In connection with this, a simulation of economic feasibility is carried out as one consideration to expand this research to the pilot scale.

The economic feasibility simulation was carried out to compare solid sludge management by secured landfill (existing) methods with the thermal process method. In its existing condition, the industrial estate manager issues around US $ 7020/month for sludge disposal to secured landfill through third-party services [11]. Also, about US $ 26,492/month is issued for the use of electrical energy in Jababeka's wastewater treatment facilities [11], as illustrated in **Figures 7 and 8**. In the proposed business model, the cost incurred for the disposal of sludge is estimated to decrease to US $ 2808/month, while the cost of electricity consumption fell to US $ 25,560/month [11]. It is related to the calculation of green energy resulted from the process is assumed to be able to substitute energy requirements as much as that produced from the gasification process [11]. In total, based on the simulation results, it is estimated that there will be a reduction in costs of up to 40% if the proposed business model is actually implemented.

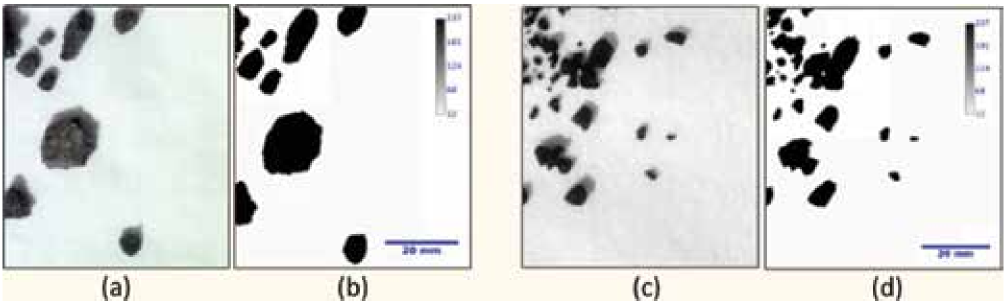

Figure 6. Average sludge particle size (a) & (b) size before pyrolysis: about 11 mm;(c) & (d) size after pyrolysis: about 4 mm (Source: Hakiki et al. [11]).

No	Items	US $/month
1	Revenue	
	Sludge disposal cost saving (to PPLI) (55% dry solid)	2808.0
	Green energy produced (expressed in US $ 0.08/kwh)	932.4
	Employment cost saving (2 people)	512.0
	Total revenue	**4252.4**
2	COGS/expenses	
	Employment cost (4 people)	1024.0
	Electricity consumption	38.5
	Fuel for start up	80.0
	Generator maintenance	400.0
	Reactor maintenance	400.0
	Miscellaneous expenses	160.0
	Depreciation on investment	886.9
	Total cost	**2989.4**
3	**Profit**	**1263.4**
4	**% Profit to revenue**	**30%**

Table 3. Benefit cost analysis of the proposed business model (Source: Hakiki et al. [11] with modification).

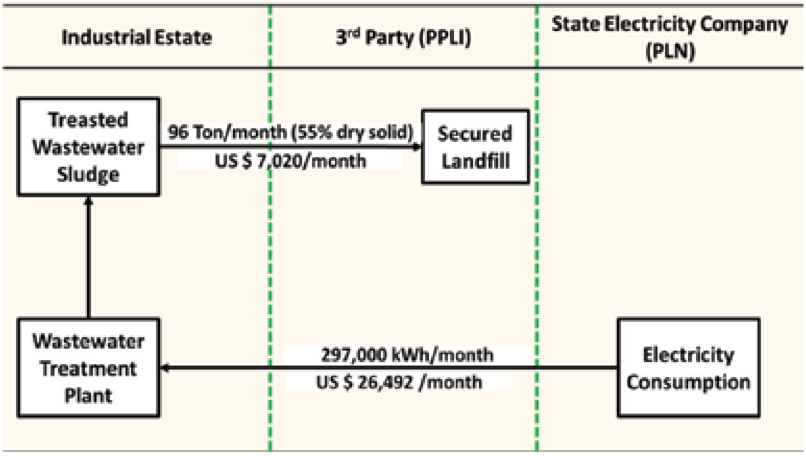

Figure 7. Existing business model (Source: Hakiki et al. [11] with modification).

In calculating and analyzing economic feasibility in the simulation, the following assumptions are made[11]: (1) The disposal costs of sludge will increase by 5% per year; (2) electricity consumption costs will increase by 3% per year; (3) employee salary costs will increase by 10% per year; (4) fuel costs will increase by 10% per year; (5) maintenance costs will increase by 10% per year; (6) miscellaneous costs will increase by 10% per year; (7) inflation rate is 6%

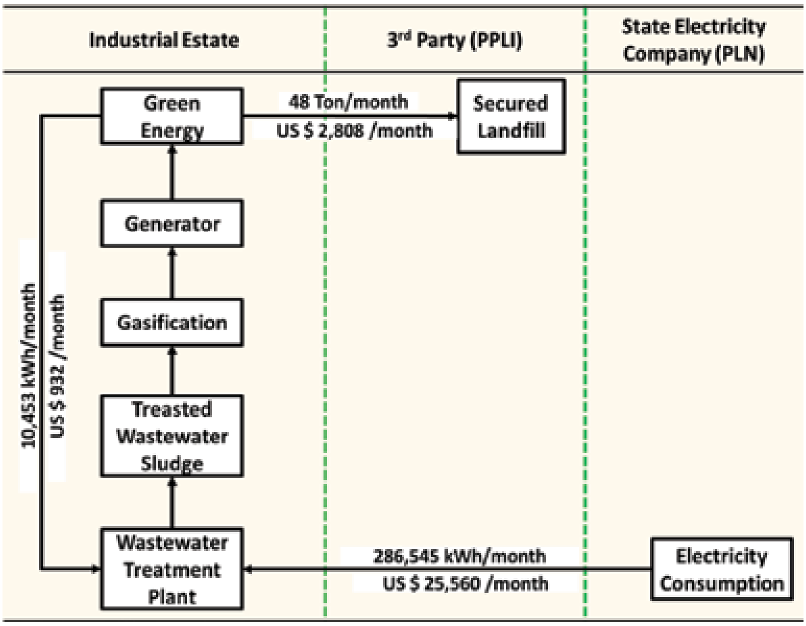

Figure 8. Proposed business model (Source: Hakiki et al. [11] with modification).

Items	Units	Value
Capacity (70% dry solid)	tons/month	75
Investment	US $	62,080.0
Lifetime of gasification unit	years	5
Profit to revenue	%	30%
Payback period	years	2.8
IRR	%	42%
NPV	US $	32,625,4
BC ratio	—	2.1

Table 4. Summary of economic simulation based on the proposed business model (Source: Hakiki et al. [11] with modification).

per year. All assumptions are based on data valid in March 2017. The summary of economic simulation can be seen in **Table 4**.

3. Conclusion

Management of wastewater sludge originating from wastewater treatment facilities can be done in several ways, including physical process (compacted into briquettes), biochemical process (anaerobic digestion), thermochemical process (pyrolysis/gasification), and extraction-transesterification (sludge as an alternative feedstock to produce biodiesel). In addition to these management methods, the last option has been commonly used in disposal to secured landfill. The last option is still seen as the best choice in terms of practicality and ease of process. In this option, the producing party utilizes the services of third parties who already have permission to manage the sludge produced. Along with increasing awareness about the decreasing reserves of fossil fuels and the increasing popularity of global warming issues, the secured landfill option needs to be reviewed further, considering that organic sludge still has the potential as an alternative energy source if managed with the proper method. Simulations carried out on wastewater sludge from Jababeka's centralized wastewater treatment facilities showed that thermochemical processing methods were quite effective in reducing sludge mass. In addition, green energy produced can also be used to fulfill some needs in treatment facilities and can be a substitute for fossil fuels. Overall, based on the results of the feasibility study simulation, it can be concluded that the thermochemical processing method can be further considered to develop into the pilot scale.

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Renewable Resources and Biorefineries presents an authoritative and comprehensive overview of biobased technologies for the production of fuels, food/feed, and materials. This book provides an insight into future developments in each field and an extensive bibliography. It will be an essential resource for researchers and academic and industry professionals in the renewable resources field.

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