Exploitation of biomass energy technologies (BETs) for sustainable future: A review

Shazia Sultana1, Ahmad Zuhairi Abdullah1,3 and Mushtaq Ahmad1,2
1School of Chemical Engineering, Universiti Sains Malaysia, Nibong Tebal, 14300, Penang, Malaysia
*Email: chzuhairi@eng.usm.my
2Department of Plant Sciences, Quaid-i-Azam University, Islamabad, Pakistan-45320

Conventional fossil-fuel based energy resources are gradually depleting and there is urgency for exploring renewable energy resources like biomass energy as they are naturally replenishing and sustainable. Recently Biomass Energy Technologies (BET) including biomass gasification, biogas, bio-ethanol and biodiesel have made impressive technical advances and are at different stages of maturity for commercialization. In this work, BETs description, status, development, management and sustenance to fulfill the energy needs, development goals and to overcome environmental issues are briefly reviewed. Past efforts, current status and future prospects regarding strategic roadmap for BETs application are analyzed while the main forms of BETs for utility scale deployment in terms of resource identification, production and commercialization are discussed. This lead to conclusions on conceptual approach, policy instruments, implementation strategy and recommendations to overcome existing barriers. The outcome of this study will be a useful guideline for policy makers to exploit BETs to overcome energy crises at global perspectives.

Keywords: Biomass energy; technology; bio-gas; bio-ethanol; biodiesel.

1. Biomass Energy

Renewable energies (RE) are in use with human society for ages and their benefits and advantages are known since then. Since the last two decades of the twentieth century, due to environment awareness and concerns about sustained development, fear of diminishing resources of fossil fuels and increase in oil prices, RE emerged as most suitable alternate of fossil fuels in the world. Among various forms of RE, biomass is one of the oldest sources of energy known to mankind. Biomass includes organic, non-fossil materials of biological origin which may be used as fuel for heat production or electricity generation [1]. In last twenty years, some biomass energy technologies (BETs) have developed to market expectations and some are nearing to it [2].

BETs have made impressive technical advances in the current era while in the meantime, the major challenges facing BETs for wider application is the costs of feedstock used as raw materials. At the same time, the energy used in fuel production is often higher than those from conventional systems [3]. However, the costs are continuously decreasing from time to time due to technical advances, manufacturing improvements and large-scale production [4, 5]. Due to these notable features, there is no denying that the BETs are growing at a very fast pace and have emerged as an attractive energy option at global level both in developing and developed countries. These technologies are viable to provide energy to those who do not have access to fossil-based, especially those living in rural areas. At national level, different countries have reasons peculiar to their national settings for switching over to biomass energy. Although the cost of biomass energy is high, the long-term environmental benefits make it attractive to society as a whole [6].

Biomass energies are growing at a very fast pace, and are significant contributor to the world energy supplies. However, still there is very less research has been done on BETs at global level. The available research is mainly restricted to justifying the need of these technologies, assessing their potential and pointing out generic problem areas for their development. It is mostly academic and generalized in nature. This critical review widely covers deployed BETs in the world and commercially matured technologies. The biomass energy technologies considered under scope of this research work are biomass gasification, sugarcane and molasses to ethanol fuel and non-edible oils to biodiesel.

It is timely to review global perspective of biomass energies to meet present and future energy needs. Their efficacy and significance for deployment and management at global level that are currently moving head-to-head with the technological advancement should be outlined. The purpose is to develop good understanding of BETs with special reference to their uses in the world. The work is expected to contribute towards generation of awareness and appreciation for the indigenous renewable energy sources and use of BETs in developing world particularly and developed countries in general [5].

2. Biomass Energy Technologies (BETs)

Bio-energy technologies cover a broad spectrum of technologies. They range from primitive (traditional charcoal making in villages, biomass-fired traditional/cottage industries by local craftsmen in rural areas, three-stone stoves for cooking) to advanced (for example cellulosic ethanol and biomass integrated gasification combined cycle, amongst others). Fig. 1 gives clear understanding of the different available technologies, the processes involved, the types of
applicable feedstock and the final products of each technology. In this chain, for a particular biomass resource, many technologies exist to convert the feedstock into a useful form of energy [7]. For development of BETs in any country, complete chain (resources, conversion-technologies, energy carriers, end-use-technologies and final usage) is necessary [2]. Nevertheless, the conversion technologies are more critical than all other links in renewable energy chain and also for overall development of biomass energies [3]. Issues usually confronted could be in terms of the feasibility of the technology, capital and operating costs, net energy gain and environmental impacts [5]. Without these technologies, any effort to successfully manage BETs will be futile. With such pivotal role in energy chain, while devising national level strategy and framework for management of BETs, it is appropriate in this research work to focus most on the conversion technologies of biomass to gasification, biogas, bioethanol and biodiesel for sustainable use.

Fig. 1 Feedstock, processes and final products of biomass energy alternatives.

3. Biomass Gasification

3.1 Technology concept, resources and environmental impacts

Biomass gasification is a thermo-chemical process in which biomass is heated in a restricted supply of air to produce an energy-rich gas (mainly contains carbon monoxide and hydrogen). This produced gas can be used as a low-carbon fuel to run an engine and generator to provide electricity or burned for heating or used as feedstock in the production of various chemicals. This partial oxidation of biomass takes place at sufficiently high temperatures, typically in the range 800–900 °C. However, the produced gas has low calorific value (about 4–6 MJ per N m³) [4] so that the net energy gain from such processes is questionable. The positive point is the gas can be improved and standardized in its quality and is easier and more versatile in its use than the original biomass. Gasification is a robust, proven, commercially available and mature technology that can be operated either as a simple, low technology system (based on a fixed-bed gasifier), or as a more sophisticated system using fluidized-bed technology. Significant research progress on related system has taken place worldwide and the net energy gain from such system has been successfully improved so that it is currently achieving sustainable level [2].

Common types of biomass resource used for biomass gasification include forestry, agricultural residues, and the biogenic component of municipal residues and wastes. The potential of biomass resource can be evaluated based on the
land available for the dedicated crops, the availability of natural forestry as well as agricultural residues and wastes. The gasification technology has good potential to assist the development of rural economies in the third world countries by providing the electricity produced from the local biomass sources [8]. However, in urban and more developed areas with better access to higher technologies, such approaches are deemed impractical and other alternatives should be offered [2].

Gasifiers consist of mainly two different types i.e. fixed bed and fluidized bed with many variations within each type. The fixed bed gasifier is the traditionally used method and operated at temperatures around 1,000 °C. Depending on the direction of airflow, the fixed bed gasifiers are classified as updraft or downdraft (Fig. 2). Fluidized bed gasifiers are generally used for coal gasification [4]. This design gives uniform temperature distribution in the gasification zone which is clearly its principal advantage over traditional fixed bed design. Two main types of fluidized bed gasifier are circulating fluidized bed and bubbling bed. The properties of the biomass feedstock and its preparation are key design parameters in selecting the gasifier system. Fixed-bed gasifiers are simpler but they usually produce low calorific value gas with high tar content [5].

![Fig. 2 Updraft and downdraft Gasifiers.](image)

At present, United States, Brazil, Germany, China and Sweden lead the world in terms of installed biomass power capacities. Other players include United Kingdom and Japan. Japan generated an estimated of 10 TWh with biomass in 2010. EU electricity production from solid biomass tripled between 2001 and 2009, and by early 2010 some 800 solid biomass power plants (an estimated 7.1 GW) were operating in Europe. Growth of biomass for power and heat in the EU has been driven greatly by supportive policies. In many countries, the policies are accompanied by taxes on fossil fuels or carbon dioxide emissions as well as regulations that require reductions in land filling of organic waste as practiced by EU nations currently [9].

Biomass offers short and long-term economic advantages. The use of locally produced resources proportionally reduces the need to import oil or coal from other regions or countries [2]. Development of local resource, technology, deployment and infrastructure generates employment in the cultivation, harvesting, and processing of biomass. Biomass is a renewable energy source so long as the growth of new crops and trees replenishes the supply [4]. It is regarded as a carbon neutral energy source as it releases only CO2 that is in fact, captured during its growth and an equivalent amount of CO2 is recaptured in the re-growth. In that sense, biomass can greatly contribute to CO2 emissions reductions which are its clear advantages when compared to the use of fossil-derived fuels [5].

### 3.2 Land and material requirements

Production of biomass does give rise to several concerns. Deforestation is a major problem in the developing world. Although it has decreased over the past decade, it continues at an alarmingly high rate in many countries [10]. Overall the use of biomass systems to offset fossil fuels significantly reduces or eliminates sulphur dioxide emissions (which cause acid rain) and a variety of other harmful emissions including nitrogen oxides and particulates. Thus, their use
addresses local and global environmental concerns. However, there are also emissions from the biomass plants themselves including particulates and NOx that must be controlled within the standards specified by environmental protection authority. Similarly, methods for ash removal, storage and offsite disposal should be put in place so that the produced ash does not cause adverse environmental impacts. The appropriate treatment of wastewater produced in the power generation and disposal of the treated water from the plant also needs special attention [5].

4. Biomass conversion to biogas via anaerobic digestion

4.1 Technological concepts, resources and environmental impacts

Anaerobic digestion is a complex biochemical processes under favourable conditions of moisture, temperature and absence of oxygen. Through a series of very complex reactions, the organic materials are decomposed by a wide range of micro-organisms with various functions, generating a gas mixture of methane, carbon dioxide and other gases. Main constituents of biogas are usually methane (CH\(_4\)) 60-65 % and 35-40 % of carbon dioxide (CO\(_2\)). It may also contain traces of hydrogen (H\(_2\)), nitrogen (N\(_2\)), water vapour (H\(_2\)O) and hydrogen sulphide (H\(_2\)S) depending upon biomass resource. About 90 % of organic material is converted into biogas and the remainder is consumed by the micro-organisms themselves [4]. It is a commercially proven technology and is widely used for treating organic wastes with high moisture contents (i.e. over 80–90 %) [11]. The simplicity and modularity of design, construction and operation and the variety of uses for the biogas product, make this technology well suited for small-scale applications [4].

![Fixed dome biogas plant.](image)

Biogas plant convert organic materials (particularly cattle dung) into a biogas and enriched organic fertilizer [4]. Two typical construction designs of the biogas plants are the floating drum-type and the fixed dome-type [11]. The produced biogas can be burned to generate electricity and heat or to be used as transport fuel. It can also act a raw material to industries (like fertilizer industry) or it can be purified and injected into the gas grid.

China had more than 40 million biogas plants/systems by year 2011. They added about 22 million new biogas systems between 2006 and 2010. India also added 60,000 small biogas plants during 2010 for a total of 4.3 million plants nationwide that are used to meet energy needs mainly for cooking. Meanwhile, Vietnam has more than 100,000 biogas systems by 2010. Other Asian countries like Cambodia, Laos and Indonesia have smaller number of programs, but overall the use of small-scale biogas plants is on the rise. Over the years Nepal has also steady increased in the number of its biogas program. The nationwide estimated number is 225,000 biogas plants for household use. In Europe, purified biogas is injected into gas pipelines to partially replace consumption of natural gas. Purified biogas (biomethane) is also increasingly injected into pipelines (particularly in Austria, the Netherlands, Sweden, Switzerland and Germany) that caused significant saving to the consumers. Germany leads the Europe where in 2010, 44 plants were injecting into the gas grid. About 20 more plants are in near completion phase currently [9]. The use of biogas helps in reducing the demand of firewood, thus, reducing pressure on the environment due to excessive deforestation. In rural areas, biogas use saves time for women which they use to spend on collection fire wood. Additionally the use of biogas as fuel in rural areas saves the people from the pollution caused by the fire wood and other fuels. Biogas is a carbon neutral fuel. Its burning does not add any additional greenhouse gasses (GHG) to atmosphere as is the case with fossil fuels. Rather, the use biogas produced in anaerobic digesters as fuel can save the methane (an important GHG) from being added into the atmosphere [4].
4.2 Land and material requirements

Biogas digesters based on the anaerobic digestion technology are commonly being made with ordinary and commonly available materials. They do not require any special materials or consumables during their manufacturing and operation. Some issues with use of biogas for power generation are such as:

- Resource supply for the organic waste, reliability of the plant and initial cost for the owners in rural areas.
- Conversion efficiency of different feedstock is different so that users need to be educated on this for optimum return on their investment and effort.
- Costs related to operations and maintenance of power plants are usually higher than the coal and natural gas fired plants and they need to be reduced.

5. Biomass Fermentation to Ethanol

5.1 Technology concept, resources and environmental impacts

Biofuels are produced from plant juices/oils, sugar beets, sweet sorghum, cereals, organic waste and the processing of biomass. Biomass can be converted into ethanol and used as a transportation fuel. There are many processes/technologies that can successfully convert biomass into ethanol [12, 13]. In sugar mills, sugarcane is crushed to extract cane juice. This juice is clarified by removing any impurities and boiled to convert into syrup. Then, it is seeded with raw sugar crystals in a vacuum pan and boiled until sugar crystals grow. The crystals are separated from the syrup by centrifugal process which is repeated many times. The remaining syrup after extraction of crystals is called molasses. It contains 45-50 % of fermentable sugars. The sugar contents in molasses are converted to ethanol in the fermentation process. Molasses itself is nowadays traded as a commodity. The conversion of molasses to ethanol consists of following main steps [12];

1. Molasses is diluted with water at a volume ratio of 1:5 (molasses: water). If nitrogen content of molasses is small, it is added with ammonium sulphate to provide enough nitrogen to yeast. The fortified molasses is further added with small quantity of sulphuric acid as acid favours growth of yeast but kills useless bacteria.
2. The prepared solution is received in a large tank and yeast is added to it at 30 °C and kept for 2 to 3 days. During this period, enzymes (sucrase and zymase) in yeast will convert sugars into ethyl alcohol.
   \[
   \text{C}_{12}\text{H}_{22}\text{O}_{11} + \text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + \text{C}_6\text{H}_{12}\text{O}_6
   \]
   \[
   \text{C}_6\text{H}_{12}\text{O}_6 + \text{Yeast} \rightarrow \text{C}_2\text{H}_5\text{OH} + 2\text{CO}_2 + 28.7 \text{kcal}
   \]
3. Alcohol obtained from fermentation is usually about 15 % to 18 % pure. With distillation, it is converted into 95.5 % pure alcohol which is known as rectified spirit. The rectified spirit is then dehydrated (using molecular sieves) to produce absolute ethanol.

Biomass resources for production of ethanol are huge and globally abundant but are subject to competition with other uses. Typical feedstock used in these processes of first generation ethanol conversion technologies include sugarcane juice, sugar beets and starch-bearing grains such as corn, sorghum and wheat. Primarily, ethanol is possibly used as fuel in three ways. It is used as an additive to gasoline for enhancement of octane and oxygen (up till 25 % in volume of anhydrous ethanol) or used in neat-ethanol engines. Otherwise, it can be used as a second fuel in flexible fuel vehicles (FFVs) which are designed to operate on any mixture of bio-ethanol and gasoline (up to 85 % by volume of ethanol). Currently, biofuels are used almost exclusively for road transport and ethanol accounts for about 75 % of global production of bio-fuels [14, 15]. World annual ethanol production increased from 67 billion litres in 2008 to 76 billion litres and 86 billion litres in 2009 and 2010, respectively. The United States and Brazil currently account for 88 % of global ethanol production [15]. In 2010, the United States overtook Brazil to become the world’s leading ethanol exporter. Other major producers of ethanol are China, Canada, France, Colombia, Poland, Spain, India and Thailand. In Brazil, ethanol from sugar cane accounts for 41.5 % of light duty transport fuel during 2010. In United States currently, around 90 % of gasoline has ethanol blending [9].

The use of ethanol as a fuel shall reduce the environmental pollution, strengthen agricultural economy, create jobs, reduce fossil fuel requirements, and thus, conserve a major commercial energy source. For sugarcane or corn (like any other agricultural produce), the overall production cycle includes the use of fossil fuels to drive machinery, to produce fertilizer and pesticides, to provide process heat for bio fuel production etc. It has been debated that it takes more fossil energy to produce the same amount energy compared to that derived out of the ethanol produced from the sugarcane or corn. However, now the consensus is that ethanol from sugarcane has positive energy balance [15]. In Brazil, the energy balance is 8 times positive. In addition, sugarcane ethanol CO2 life cycle emissions are about 80 % lower than those of fossil gasoline. It should be highlighted that the majority of these emissions are from the production of the sugarcane itself [16].

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5.2 Land and material requirements

Diverting food crops and resources to ethanol fuel production can have adverse effects such as an increase in food prices and hunger in poor countries. Impact of land utilization by bio-energy crops is measured on the basis of land occupation by these crops and it is commonly measured in terms of hectare-years. On average, about 0.39 ha area is required for sugarcane farming to produce 1000 L of molasses for ethanol production [17]. Some research works indicate that at global level, enough land is currently available for both food and energy crops. Moreover, in South America, systematic planting of energy crops for ethanol has implemented on cleared land. This practice can have adverse social impacts on the local population and may lead to soil erosion and loss of biodiversity. Such impacts can be reduced by using marginal or under-utilized lands [16].

6. Biomass to Biodiesel

6.1 Technology concept, resources and environmental impacts

Any feedstock that contains triglycerides and/or free fatty acids can be theoretically converted to biodiesel. Transesterification is the most common reaction pathway to produce biodiesel but a number of alternative processing technologies for the production of biodiesel do exist. Biodiesel is obtained by transesterifying the triglycerides with methanol or other alcohols. Methanol is usually preferred because it is cheap and abundantly available. To increase the reaction rate a catalyst is added, usually sodium hydroxide (NaOH) or potassium hydroxide. Other bases or some acids can also be used as catalyst. However, base-catalyzed reaction has higher reaction rate [18, 19]. The reaction takes place at 60-70 °C and at atmospheric pressure. Following simplified equation indicates the generic production process of biodiesel and proportions of chemicals used therein.

\[
\text{Triglyceride + Alcohol} \rightarrow \text{Mixture of fatty esters + Glycerol}
\]

There are several technologies that can be used to produce biodiesel. Also, there are also various approaches to the esterification process. Such variations result in different operating requirements such as water use requirements, and operating modes. The choice of technology depends upon the desired plant capacity, feedstock type and quality, alcohol recovery and catalyst recovery [21]. Under various conditions/requirements, these technologies can be combined into a number of ways. Many of these technologies are well-established with commercial scale yields. These technologies are generally referred to as first-generation technologies. Vegetable oils, animal fats, and recycled greases are the primary raw materials for biodiesel production. Soya bean and palm oil are two most traded oils in the world. Soya oil is mostly used in the United States while Indonesia and Malaysia usually depend on palm oil for biodiesel production [22]. Due to the argument against the use of food crops as raw material for energy generation that can create an imbalance in global food supply chain, attention is currently focused on use of non-edible vegetable oils for biodiesel production. Many such resources have been identified such as used cooking oil, Jatropha oil, Karanja oil etc. [20, 21, 22].

Presently, the main usage of biodiesel is in road transport. In 2010, the global biodiesel production was 19 billion litres. The EU is leading the world in biodiesel production (245 plants with an annual capacity of 25 billion litres but the annual production stood above 10 billion litres). Germany, Brazil, Argentina, France, the United States, Thailand, Canada and Indonesia are the leading producers of biodiesel. From 2005 to 2010, biodiesel achieved second highest growth rates among all renewable technologies. However, its growth in 2010 slowed down due to oversupply [9].

Biodiesel is a sulphur free fuel. Engines using biodiesel are reported to be less smoky and emit no sulphur, fewer particulates and aromatic hydrocarbons as well as lower level of carbon monoxide than that of conventional diesel. However, emissions of NOx are slightly high compared to gasoline engines [23]. In absence of aromatic hydrocarbons, the emissions are relatively less toxic. Overall, the use of biodiesel shall produce lower level of undesired effect to the environment. It is safer to handle as it has higher flash point and does not produce explosive air fuel vapours. It is also biodegradable and less toxic. Biodiesel has similar storage requirements as of petroleum diesel. Therefore, no special storage infrastructure is required [24]. The use of biodiesel is expected to offsets GHG emissions [25, 26].

6.2 Land and material requirement

Presently, the main feedstock for biodiesel production is vegetable oils. The utilization of vegetable oil crops to biodiesel production has increased the prices for such crops in recent years. There are concerns that such a trend shall increase food prices, and thus, may have serious effect especially on third world countries. Such concerns need to be resolved with more research works and policies. These could include the use of under-utilized lands, development of better production technologies, adopting modern techniques in crops plantation to provide better productivity, making use of wastes as well as forestry industry residues.
7. Conclusions

Biomass energy technologies (BETs) hold good promise to meet the world’s growing energy needs. These technologies have enormous resource potential, growing phenomenally, advancing technologically and getting commercially mature. Realizing the poor management of BETs in the past, this work analyzes and outlines the needs for a comprehensive technology management framework. So, many essentials of such framework have been reviewed and proposed. These includes national objectives, fundamentals and essentials for BE technology management and law. Analysis of the current policy as well as suggestions for relevant future policy are offered. All such implementations are critical for both on-grid and off-grid applications of BEs for a more sustainable future.

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