

## Research Article

# Towards Circular Economy through Waste to Biomass Energy in Madagascar

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Received 8 May 2021; Accepted 28 May 2021; Published 8 June 2021

Academic Editor: Shaohui Wang

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Biomass energy, contributing to about 80% of the total energy supply, is considered an important energy source in Madagascar. Although around 80% of energy use comes from biomass energy, the current application method of biomass in Madagascar is still in the earliest stage, which is not safe and sustainable. This is because the main form of biomass energy used in Madagascar is still solid charcoal and wood, and the technology is limited. Thus, it is necessary to search for better ways to utilize biomass energy in Madagascar because of high prices of traditional energy carriers and massive environmental pollution. This paper reviews the following: (1) a variety of available biomass wastes for energy in Madagascar including farming residuals, animal wastes, and forest wastes, as well as urban and industrial organic wastes; (2) advanced technologies, such as gasification, torrefaction, and fermentation, that can convert these wastes to biomass energy in forms with higher energy efficiency such as biogas, biocoal briquette, and ethanol fuel, which can not only help to achieve resource utilization of wastes and circular economy but also ease the energy crisis faced by Madagascar; and (3) Madagascar focused on the development of biomass energy with strategic policies and programs. International assistance also contributes to future promotion of biomass energy. It identifies several areas where research is urgently required to adopt instrumental policies to ensure that both rural development objectives and renewable energy targets are met with financial support from the government and international assistance.

## 1. Introduction

Energy security and declining of fossil fuel resources have led to several environmental problems and have attracted widespread concerns from many economies around the globe, both developing and developed [1, 2]. Demand for renewable energy as well as associated services, to meet the requirement of essential human needs and further socio-economic development, is increasing over time [3–5].

Biomass energy can be produced from various biomass stocks including forest, agricultural products, livestock, crops, and organic wastes [5–7]. It is a renewable source of clean energy containing a complicated mix of carbon, nitrogen, hydrogen, and oxygen. Many countries have

identified the socioeconomic value and environmental value of biomass energy, and they have promoted the use of biomass energy through instrumental policies as well as financial support [8–11].

Madagascar, an island country located at the southern tip of the Indian Ocean, is one of the least developed countries globally [12]. Figure 1 shows the percentage share of various energy resources in Madagascar up to September 2018 [13]. Electricity is still scarce in Madagascar, in which only about 20% of the population has access to this form of modern energy [13, 14]. In rural areas, only about 5% of the population has access to electricity [15]. Although there is a rich reserve of oil in Madagascar, its fields are untapped [16]. The major source that fulfills the energy need in Madagascar

is biomass energy, accounting for 80% of the total energy consumption [13].

Biomass energy consumption is in practice in Madagascar since ancient times. Figure 2 shows the composition of biomass energy used in Madagascar [13]. Firewood is the most important source of biomass energy in Madagascar accounting for 85% of the total amount. Charcoal makes up 12.5% of biomass energy consumption. Biomass energy from other sources only contributes 2.5%. These data indicate that the application of biomass energy in Madagascar is still in the earliest stage [17]. Most biomass energy is used directly for cooking from the forest. It is actually unsafe and not environment-friendly to utilize the biomass energy in the solid form directly as it will generate a considerable amount of pollutants like ash and smoke [18, 19]. Meanwhile, residents have to keep cutting down the forest to meet their energy needs, resulting in severe loss of biodiversity and land desertification [20, 21]. Therefore, conversion of waste to biomass has been encouraged by the Madagascar government to address the associated problems [22, 23]. Many subsidies are offered to support the development of waste to biomass. Application of advanced biomass technology also promotes the future utilization of biomass energy [24–26].

This paper identifies a variety of available waste resources, which can be converted to biomass energy in Madagascar. The objective of this study was to conduct a systematic review of applying advanced technologies for conversion of waste to biomass energy and also biomass electricity generation in Madagascar. Government policies to support the promotion of biomass energy are mentioned as well. Biomass energy seems to be one of the best renewable energy sources to achieve a circular economy for Madagascar.

## 2. Available Biomass Wastes in Madagascar

Biomass energy refers to the energy stored in biological organic matter in the form of chemical energy transferred from solar energy through photosynthesis of plants [27]. All energy sources from plants and animals in organic matter, except fossil fuels, are biomass energy [28]. They usually include wood, forest wastes, farming residues, aquatic plants, animal wastes, energy crops, and urban and industrial organic wastes [29–31]. Conversion of waste to biomass energy is the way for sustainable development and realizing the virtuous circle of ecology. These various available waste sources for biomass energy production have different production characteristics and different energy efficiencies, from the perspectives of processing methods, energy utilization methods, clean production levels, etc.

**2.1. Farming Residues.** Farming is the most important industry contributing about 30% of the total GDP in Madagascar. About 51.35% of the cultivated land produces primarily rice, followed by cassava and then corn [32, 33]. Industrial products, such as cotton, spice, coffee, and flax, have been developed for a long time in Madagascar. Massive

agricultural residues, such as grain dust, wheat straw, and hazelnut shell, storing a considerable amount of biomass energy, are therefore produced [34]. Based on survey and data collection, output of each crop and available residues each year [35] are compiled in Table 1.

These farming residues can provide a considerable amount of raw materials for biomass energy production and ease the energy shortage in Madagascar.

**2.2. Animal Wastes.** Animal husbandry is also an important economic sector of Madagascar, whose beef and buffalo output in 2019 totaled 161,902 tonnes, poultry output 85,388 tonnes, and eggs' primary output 25,393 tonnes [36]. The livestock inventories of cattle of Madagascar ranks first in Africa, known as the "country of cattle" [36, 37]. These animals generate a huge amount of wastes like dung every day. At present, the disposal method of animal waste in Madagascar is mainly to directly dump or use as biological fertilizer, which not only fails to make effective use of biomass but also easily causes excessive microorganisms and eutrophication in water bodies [38]. In fact, animal wastes can be regarded as a significant source of biomass energy in Madagascar [39]. If the animal waste is converted into renewable clean energy, it can not only make full and effective use of resources to relieve the energy shortage but also reduce the environmental pollution caused by the waste.

**2.3. Forest Wastes.** Almost all of Madagascar is located in the tropical region in which climate is affected by the wind system and altitude. The southeast coast has a typical tropical rainforest climate with an average annual temperature of 24°C and an annual precipitation of 2000–3000 mm. It is hot and humid all year round and seasonal change is not obvious. Dense tropical vegetation and forests grow here. Statistics show that over 20% of the land in Madagascar is covered with forests [40–43]. A large amount of forest wastes are generated, including scattered timber, residual branches, leaves and wood chips in forest tending and thinning operations; branches, sawdust, tops, sheeting, and cutting heads in wood harvesting and processing; and forestry byproducts of waste such as shells and nuts [44–46]. As for these forest wastes, Madagascar generally adopts the traditional treatment methods of landfill and incineration. Only a few parts can be resource-utilized [47]. In fact, forest waste contains a large amount of lignin, cellulose, hemicellulose, and some other organic substances [48, 49], which can be converted to biomass energy. It is not only environmentally friendly but also economical.

**2.4. Urban and Industrial Organic Wastes.** Madagascar's industrial base is very weak. Apart from a small amount of mining, Madagascar's industry is dominated by light industry. Agricultural products' processing industry accounts for a large proportion of Madagascar's industries, whose products mainly include edible oil, canned food, flour, sugar, tapioca powder, meat, and fish. In recent years, the enterprises in the labor-intensive export duty-free areas mainly

focusing on needles and textiles have developed rapidly [50–52]. Most enterprises are located in the industrial area in the south of Antananarivo [52, 53]. Specific industrial structure and relatively concentrated enterprise distribution make it significant and convenient to recycle and resource-utilize the urban and industrial organic wastes to produce biomass energy. However, the resource rate of Madagascar's urban and industrial wastes is still very low. Future development of urban and industrial waste management is required in Madagascar with regard to both technologies and government policy systems.

### 3. Biomass Energy Conversion Technologies

It is clear that Madagascar has very rich raw materials for waste conversion to biomass energy through some modern technologies. This section briefly introduces several biomass energy conversion technologies, including gasification, torrefaction, and fermentation, that can be used in Madagascar.

**3.1. Gasification.** Gasification refers to the transformation process in which the pyrolysis of biomass wastes produces combustible gas combined with CO, H<sub>2</sub>, or CH<sub>4</sub>, through thermal chemical reaction under the condition of high temperature and hypoxia [54]. Gasifier is the main equipment of biomass gasification reaction. It is found that compared with solid biomass fuels such as firewood and charcoal, biogas is much more efficient [55].

Biomass stream processing (BSP) is the most common technology for biomass gasification. It is a steam-assisted thermochemical conversion process aimed at increasing the energy density of biomass raw materials, and is a promising method for converting biomass waste into high-energy biogas. It allows biomass wastes to be heated from 250°C to 400°C in an atmospheric steam environment and efficiently converted into biogas in about 1 hour [55, 56]. Figure 3 gives a schematic representation of the scale of the BSP technology [55–59]. Firstly, water is pumped by a diaphragm pump from a storage vessel into the evaporator. And then, the water flows through an electrically heated steel tube and the steam generated is heated further to reaction temperature before it is being injected as superheated steam into the reactor. Secondly, biomass is fed continuously to the electric oven. Thirdly, steam feed temperature is constantly monitored by a K-type thermocouple at the steam inlet of auger reactor. Finally, the purge stream is directed to a condenser for offline aqueous phase analysis. Biogas is therefore generated.

Uncomplicated technology and high socioeconomic and environmental benefits make it possible to develop and prompt BSP technology in developing countries. Currently, BSP technology is successfully being practiced in many developing countries such as Philippines and India, which efficiently addresses the problem of energy shortage for local residents. These examples prove that implementation of BSP technology in Madagascar is feasible.

**3.2. Torrefaction.** When biomass is directly consumed, the utilization and efficiency are very low, as it has a lower energy density than fossil fuels such as coal or diesel. Many studies have shown that the torrefaction can increase the energy density of biomass to equal to or even greater than the energy level of coal. Figure 4 shows the general reaction process of torrefaction [60–62]. The inert gas N<sub>2</sub> is injected into the flowmeter, and then it is injected into a reactor to react with the biomass. After the reaction, volatile gas is obtained and injected into the pipe device shown in the figure. Finally, the permanent gas is discharged and compressible liquid is collected.

When heat is sufficiently applied to the biomass under controlled thermodynamic conditions, torrefying occurs, causing chemical, physical, and mechanical changes in the biomass. The torrefied biomass can be cofired with coal to reduce the import of fossil fuels and the emissions of CO<sub>2</sub>, NO<sub>x</sub>, and SO<sub>x</sub> [63, 64]. This technology has been implemented in many African countries.

**3.3. Fermentation.** At present, the existing biomass fermentation modes on the market are mainly ethanol fermentation, hydrogen fermentation, and biogas fermentation [65, 66]. Compared with ethanol fermentation and hydrogen fermentation, biogas fermentation has the advantages of high conversion rate, low technology requirement, low investment and operation cost, etc. [67]. In fact, biogas fermentation has been applied in Madagascar although it has not been promoted, which indicates that biogas fermentation is very suitable for Madagascar, especially for the rural areas because of limited technology conditions but rich raw materials [68–70]. Figure 5 shows three main steps in biogas fermentation [68–70]. First of all, biomass wastes can be hydrolyzed into monosaccharides, amino acids, glycerol, and fatty acids. And then, organic acids produced in the first stage are oxidized and decomposed into acetic acid and molecular hydrogen by bacteria-producing hydrogen and acetic acid. Finally, Methanogenic bacteria convert low-molecular-weight compounds such as acetic acid, formic acid, hydrogen and carbon dioxide produced in previous stages into methane.

Ethanol fermentation is another common fermentation method in the conversion of waste to biomass energy. Figure 6 shows several steps of the production of ethanol fuel [71, 72]. Firstly, the biomass wastes are comminuted. Secondly, the raw materials such as cellulose or starch are converted into polysaccharides. Thirdly, ethanol is produced by the tricarboxylic acid cycle (TCA). And then, by distillation, the method of condensing obtains a kind of high-purity ethanol, and this whole product is converted into fuel ethanol by dewatering. Finally, the ethanol fuel and gasoline are mixed in a certain ratio to obtain fuel ethanol. This ethanol has good intermixing properties, and its physical and chemical properties are similar to gasoline, so it can be used as a novel type of clean automotive fuel-ethanol gasoline for vehicles. Through checking gasoline with a certain amount of ethanol, the content of CO and hydrocarbons was

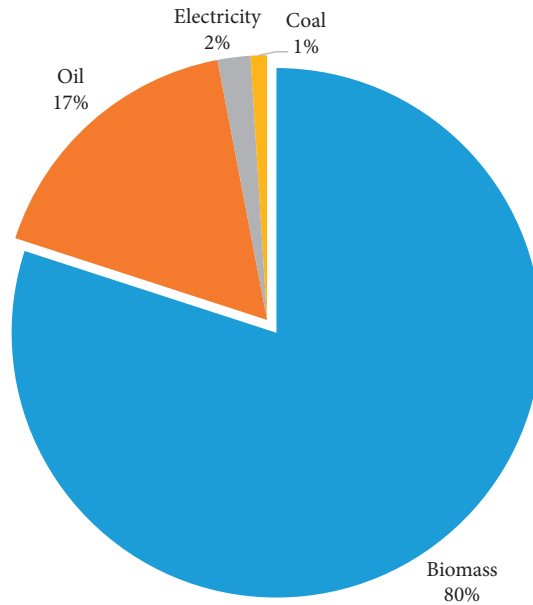


FIGURE 1: Percentage share of various energy resources in Madagascar up to September 2018.

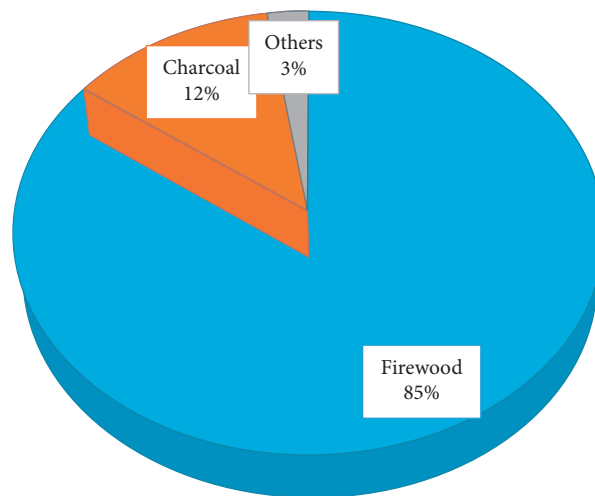


FIGURE 2: Percentage share of various biomass energy resources in Madagascar.

reduced by 20%-50% and 15%-40%, respectively, and almost no SO<sub>2</sub> emissions were detected.

In Madagascar, cassava, sugarcane, corn, and other crops are produced in large quantities, and the residues of these crops are rich in sugar liquid, lignocellulose, and starch. Therefore, these residues can provide rich raw materials for ethanol fuel production.

#### 4. Madagascar Energy Policies and International Assistance

Energy shortage is a major obstacle to business and economic and social development in Madagascar, which was caused by the previous Madagascar government that only focused on short-term requirements and simplified problems in the design of policies. Therefore, currently, the new government attaches great importance to energy security.

Madagascar has implemented a series of policies to develop the renewable energy like biomass energy in the future. International assistance also contributes to this process significantly.

**4.1. Madagascar Energy Policy.** Development of energy and emission reduction programs according to distortions between energy prices and marginal costs results in the obstacles. These are the main obstacles that Madagascar faced, and it is necessary to apply an effective energy policy to overcome this gap. It is expected to obtain the maximum return on the implementation of energy policy. The Madagascar government has placed priority on renewable energy industry in national development to attract domestic and foreign capital investment in biomass energy and other renewable energy industries.

TABLE 1: Available farming residues for biomass energy generation in Madagascar.

Crop	Residues	Output (t/yr)	Proportion (%)
Paddy	Stalks, husk	4,737,965	45.58
Cassava	Stalks	3,008,895	28.95
Maize	Stalks, cobs	441,914	3.96
<i>Ipomoea batatas</i>	Stalks	919,127	8.84
Potato	Stalks	225,850	2.17
Kidney bean	Stalks, husk	82,130	0.79
Butter bean	Stalks, husk	15,210	0.15
Peanut	Stalks, husk	59,495	0.57
Coffee	Husk, pruning and wastes	39,760	0.38
Pepper	Stalks	3,275	0.03
Clove	Fronds, pruning wastes	9,535	0.09
Vanilla	Stalks	3,910	0.04
Cocoa	Husk, fronds	7,633	0.07
Tobacco	Stalks	2,499	0.02
Tea	Pruning and wastes	311	0.00
Litchi	Husk	184,396	1.77
Sugarcane	Stalks, husk	683,166	6.57

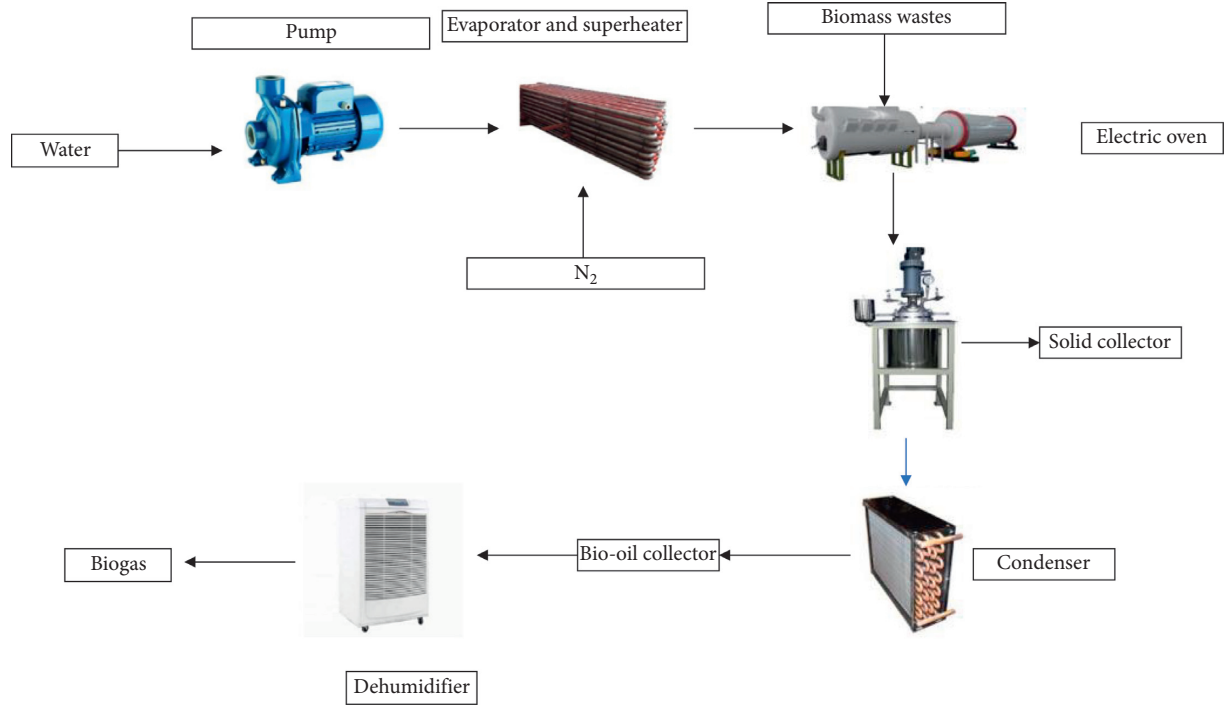


FIGURE 3: Schematic process of the BSP process.

The Government of Madagascar has announced that the imported facilities for renewable energy can get a value-added tax or can be exempted from the tariffs. Economic Development Board of Madagascar (EDBM) released a guideline “Renewable Energy Sector and Electricity Sub-Sector Actors 2019” [73]. This guideline is divided into English and French versions, covering 12 categories including government departments, development partners, financial institutions, nongovernmental organizations, law firms, and agents. It collected practical information of related institutions, including address, telephone number, website, and so on, which can provide convenience to

international investors. In addition, Madagascar tries to prompt advanced renewable technologies. For example, two cities (Ambanja and Ambilobe) were selected as renewable energy demonstration plots in 2017 and technology support and fiscal support were provided by the Madagascar Government to develop biogas power generation [74]. Since 2018, biogas has become the main energy source for local residents.

Madagascar’s fiscal 2019 budget report indicates that the Madagascar government will continue to enhance the development of renewable energy including biomass energy and achieve 50% of electricity penetration by 2024 [73].

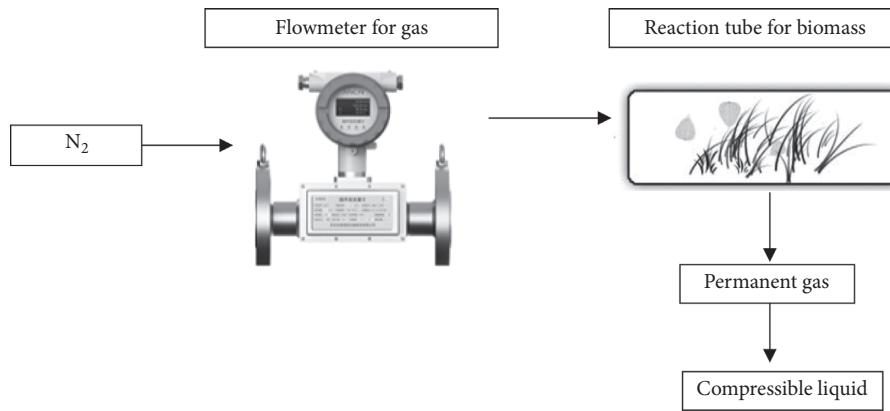


FIGURE 4: Schematic process of the torrefaction process.

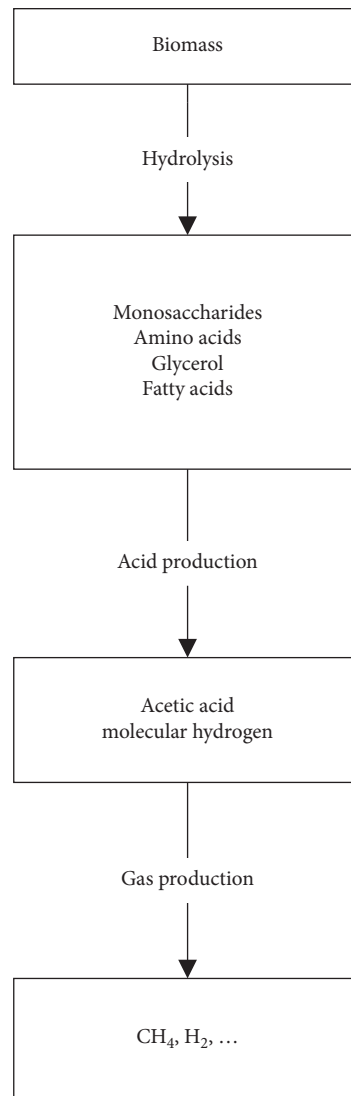


FIGURE 5: Schematic process of the biogas fermentation process.



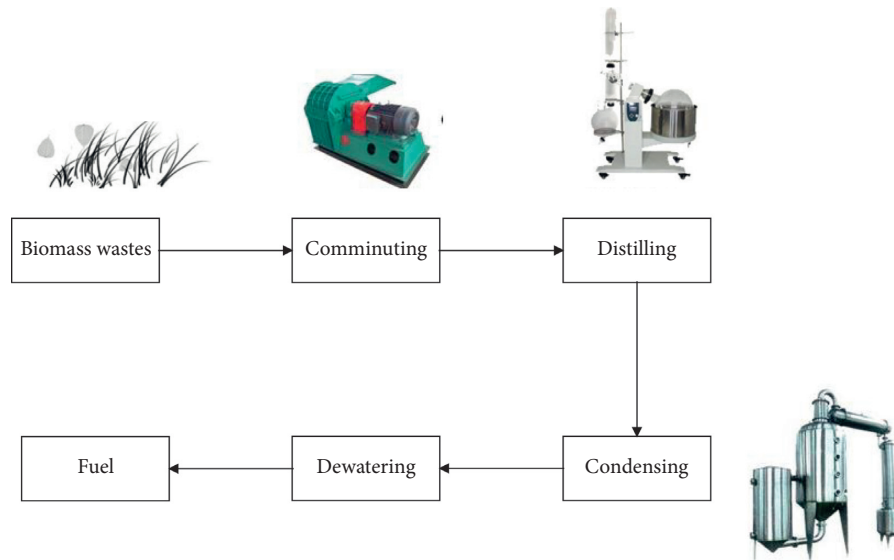


FIGURE 6: Schematic process of the ethanol fermentation process.

**4.2. International Assistance from China and Germany.** Madagascar is one of the least developed countries in Africa. Limited economic and technology conditions severely obstruct the future development of waste to biomass energy here. Therefore, international assistance helps a lot in this process. This section presents support from China and Germany.

**4.2.1. Assistance from China.** The diplomatic relations between China and Madagascar maintain steady development in recent decades. Since China and Madagascar formally established ambassadorial diplomatic relations in 1972, China–Madagascar pragmatic cooperation has achieved fruitful results [75]. The Ministry of Commerce of China proposed “the Belt and Road Initiative (B&R)” in 2013, advocating the concept of sustainable development, and it promotes Chinese enterprises to provide support to the renewable energy industry in Madagascar [75]. For example, Chengdu DeTong Environmental Engineering Co., Ltd. has built a 30-square-meter box-type human manure and municipal organic waste biogas project in Tananarive along with the Bill & Melinda Gates Foundation in 2015. The disposal capacity of municipal organic waste reached 780 kg and biogas production rate reached 0.35 m<sup>3</sup>/kg VS/d [76]. According to the Economic and Commercial Counsellor’s Office of the Embassy of China in Madagascar, China’s stock of investment reached \$766 million and the direct investment reached \$71.20 million in 2017 in Madagascar, including a large portion in renewable energy industry [77].

**4.2.2. Assistance from Germany.** Madagascar’s government has signed a memorandum of understanding with an Africa-focused financing agency (RLSF) to improve the renewable energy installed capacity through eliminating the insurance and financing pitfalls of the past. RLSF is a fund set up by Array Technology Industry (ATI) and German KfW Bank (KfW), which reduces project financing costs while

protecting developers from delays in payments, through a state-owned utility (JIRAMA) [78]. The support fund initially received \$63.2 million from the German federal ministry for economic cooperation and development. Madagascar is the sixth signatory after Benin, Burundi, Malawi, Uganda and Zambia. Previously, lots of projects may fail without guarantees. The cooperation with RLSF has a positive impact on the development of the energy industry in Madagascar; for example, the renewable energy projects obtained funds and reached the financial closure stage through the guarantees from RLSF. In addition, the amount of guarantee by RLSF and Absa Bank is equal to the income of independent generator from power station in 3–6 months. According to Vonjy Andriamanga (Minister of Water, Energy and Oil of Madagascar), RLSF is an important tool to support the development of renewable energy projects that contribute to achieve the strategic objectives set out in the energy performance contract.

## 5. Conclusions

At present, 80% of the total energy supply is from biomass energy, which is considered an important energy source in Madagascar. However, the current application method of biomass in Madagascar is still in the earliest stage, which is not safe and sustainable. Also, it is not adopted for the requirement of sustainable urban development and environmental protection [79]. Although there is a long history of using biomass energy in Madagascar, the method of application is still in the earliest stage.

Hence, this paper identified the resource and the potential of the conversion of waste to biomass energy. Biomass wastes in a wide variety and different forms are available in Madagascar such as farming residuals, animal wastes, and forest wastes, as well as urban and industrial wastes [80]. Converting these biomass wastes to energy has obvious socioeconomic benefits and environmental benefits. This paper also introduces some advanced conversion

technologies for the conversion of waste to biomass, which can be used in Madagascar. Gasification converted biomass wastes to combustible gas; torrefaction can increase the energy density in solid biomass energy and be used to produce biocoal briquette; fermentation can transfer these biomass wastes to biogas or ethanol fuel. Advanced conversion technologies can not only improve the efficiency of energy utilization but also reduce the cost of power generation [81]. Development and promotion of waste to biomass energy require the participation of the government. The Government of Madagascar has set a series of policies, including tax preference and fiscal subsidies, to encourage the application of renewable energy like biomass energy. With the limited economic and technology conditions, support from other nations such as Germany and China also plays an important role in the conversion of waste to biomass energy process in Madagascar.

In conclusion, conversion of waste to biomass seems to be the feasible approach to address the energy problem and achieve circular economy in Madagascar although it still has a long way to go.

## Data Availability

All the datasets generated for this study are included within the article.

## Conflicts of Interest

All the authors declare no conflicts of interest.

## Acknowledgments

The authors wish to acknowledge the financial support provided by the Scientific Research Foundation of Guangxi University (Grant no. XJZ140395).

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